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STUDY TO DETERMINE REQUIREMENTS FOR UNDERGRADUATE PILOT TRAINING RESEARCH SIMULATION SYSTEM (UPTRSS)

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A. GERBER, et al.

Link Group

Singer-General Precision, Inc.

Binghamton, New York

TECHNICAL REPORT AFHRL-TR-68-11

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FOREWORD

This report summarizes the results of a study conducted by the Link Division of Singer Company, Binghamton, New York, under Contract No. F 33615-68-C-1604 to determine the requirements for an Undergraduate Pilot Training Research Simulation System (UPTRSS) to be procured by Aeronautical Systems Division (AFSC) for use by the Air Training Command. The report was submitted on 13 January 1969. The Contract Monitor was Don R. Gum of HRTS.

This technical report has been reviewed and is approved.

DR. G. A. ECKSTRAND
Chief, Training Research
Division
Air Force Human Resources
Laboratory

ABSTRACT

In order to provide a sound basis for the preparation of specifications defining the requirements for the Undergraduate Pilot Training Research Simulation System (UPTRSS), a comprehensive study was made of all aspects of current and projected simulator technology and those techniques of simulation and training which appeared to offer the greatest utility for research purposes were analyzed in detail to determine the form and extent of the capability in each area (e.g., aircraft systems simulation, motion simulation, visual simulation) which should be specified for the facility. To assure the Air Force the widest possible latitude in its eventual selection of the equipments to be provided in the facility, alternative approaches of varying levels of complexity are described in a number of areas and the tentative preliminary design requirements set forth in each area are qualified as necessary, to permit them to be considered in the light of subsequent decisions by the Air Force regarding research objectives, training objectives, and level of expenditure.

(Distribution of this abstract is unlimited.)

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PROBLEM

An Advanced Development Program to demonstrate the maximum effective utilization of simulators in undergraduate pilot training, and to define the future generation simulators for undergraduate pilot training was initiated in February 1968. Since there are no simulators available today which are capable of supporting such an advanced development program, it is necessary to first develop the required simulation equipment.

APPROACH

A study was undertaken, from which this report resulted, whose objective was to determine the extent of the experimental program to be conducted and to determine the necessary simulation equipment to support this program. The study first determined the minimum performance requirements independent of equipment considerations, and then recommended the equipment which could best fulfill these requirements. A basic ground rule was to recommend latest state-of-the-art equipment or modest extensions thereof, rather than unproven techniques.

RESULTS

The recommendations were for two simulators for each of the two Air Training Command aircraft. Each simulator is to have a visual system adapted to certain phases of the training program, six-degree-of-freedom motion, sustained "G" simulation, a conventionally instrumented instructor's console, an advanced instructor's console, an experimenter control console, and activated from a general purpose digital computer.

CONCLUSIONS

The ground work has been laid for the development of an advanced simulation system for use in undergraduate pilot training. The system has been defined, and the technology is capable of meeting the requirements in most of the areas.

DON R. GUM
Training Research Division
Air Force Human Resources Laboratory
Contract Monitor

1. INTRODUCTION

This report contains the results of the engineering effort expended during Phase II of the UPTRSS study program. The initial effort, Phase I, was devoted primarily to determining the areas in which research will be performed in the facility and included much of the human factors effort in this program. The functions of the UPTRSS were outlined as follows, not necessarily in order of priority:

1) To provide the information necessary to define the performance characteristics and design requirements of simulators that could contribute maximally to the undergraduate pilot training program as well as other flight training programs.

2) To investigate the efficiency and efficacy of new training techniques and methods that can best be implemented through innovations in the design of flight simulators or other ground-based training equipment.

3) To provide a research environment wherein essential pilot skills and capabilities can be identified and analyzed to provide information required to evaluate approaches to undergraduate pilot training.

4) To provide the facilities necessary to conduct research in related areas such as selection, screening, placement, performance measurement, and retention of proficiency.

5) To provide the facilities necessary to support human engineering developments related to training, such as head-up displays, safety, and sensory cueing.

6) To provide an environment that will permit preliminary evaluations of innovations in program, scheduling, sequences of training, automated training, and alternate roles for the instructor.

7) To support research that will assist in determining the characteristics of future training aircraft for the UPT program.

Phase II has been primarily an engineering effort, with tradeoff studies and analyses performed to determine the best equipment to meet the research facility requirements. State-of-the-art considerations were heavily weighted in the analysis of simulation equipments and techniques that were best suited to meet the research facility requirements.

Periodic meetings were held throughout the Phase II effort with senior simulation engineering personnel to ensure that overall systems considerations were not neglected. It became clear early in the program that the visual

requirements were extremely difficult to fulfill because of the large amount of contact flying performed in the UPT program and the large fields of view available in the T-37 and T-38 airplanes. Also, the maneuvering envelope of these airplanes in extensive and a considerable portion of the flight curriculum consists of maneuvering the aircraft through wide ranges within the aircraft's performance envelope.

The characteristics of the training maneuvers were separated as follows and the training requirements in each category defined, discussed, and studied:

1) Airwork and aerobatics
2) Circling approach
3) Takeoff and landing
4) Formation
5) Navigation
6) Low-level flight
7) Night flight
8) Instrument flying

For each of these categories, state-of-the-art equipment capability was evaluated and is discussed in this report. The scope of the evaluation was considerably influenced by the requirements established in the Phase I report. To this end, the study report contains detailed discussion and evaluation of required capabilities in the following areas:

1) Crew Station Configuration (Section 2) - A discussion of the trainee station and instructor station instrument and cockpit requirements for the T-37 and T-38 aircraft simulators.

2) Complexity of Aircraft Simulation (Section 3) - A detailed discussion of the mathematical complexity of the simulation models with consideration given to the capability of degrading the fidelity of simulation.

3) Instructor and Research Consoles (Section 4) - Careful consideration of the requirements and equipment at the instructor, pilot, and research stations to facilitate comprehensive training and research to be performed while also allowing the equipment being used to be evaluated. Advanced techniques using CRT displays to monitor or change a given simulation problem are discussed.

4) Computational Function (Section 5) - A discussion of the computer requirements for the UPTRSS and an evaluation of equipment capable of fulfilling these requirements accounting for flexibility and future growth.

5) Mathematical Models (Section 6) - The importance of modularity of mathematical models, and the capability for insertion of malfunctions is discussed.

6) Research Facility Software Requirements (Section 7) - Software capability, which emphasizes flexibility, ease, and speed in program change, is discussed in detail.

7) Motion Simulation (Section 8) - A discussion of the requirements for the simulation of motion cues and sustained acceleration for the T-37 and T-38 aircraft maneuvers is given.

8) Visual Simulation (Section 9) - A detailed evaluation of the exacting visual equipment requirements for each of the training categories listed previously (airwork and aerobatics, etc.) is given. State-of-the-art equipment capabilities are evaluated, and four separate visual simulation systems are recommended.

9) Other Environmental Simulatin (Section 10) - A discussion of the requirements and equipment capabilities for aural and olfactory simulation.

10) Advanced Training (Section 11) - Adequate capability to perform research in improving the rate of learning of student pilots is essential. This flexibility is reflected in the computer and other peripheral equipment recommendations. This section also reviews the current and expected developments in advanced training techniques.

11) Site Requirements and Facility Configuration (Section 12) - This section discusses suggested facility configurations and requirements for housing the T-37 and T-38 simulators. Consideration is given to the possibility of incremental procurement.

12) Maintenance Considerations (Section 13) - A detailed discussion is included of maintenance features which should be incorporated in the UPTRSS.

13) Vendor Survey (Section 14) - In an attempt to ensure that present state-of-the-art techniques were fully evaluated, an extensive vendor survey was undertaken. However, this survey was of limited usefulness in determining the state state of the art. The leading companies in the simulation industry are apparently reluctant to disclose any specific information concerning their equipment, even though much capability information of a general nature is known.

An important conclusion of the study was that as far as can be ascertained, no visual equipment presently in existence can fully meet the research facility requirements.

Based upon the results of the study, requirements for four separate simulators were evolved, two T-37 simulators and two T-38 simulators. The number of simulators recommended was primarily a function of the eight training maneuver categories and the visual equipments capable of simulating each maneuver. The equipments specified are compatible with the training curricula for the T-37 and T-38, while providing a maximum of maneuvering simulation within each machine.

The study recommendations reflect the state of the art, and conservative extensions of that art, in developing the concepts for the research facility. The facility that resulted from the study effort is believed to represent the capability that is required to meet the goals of the UPTRSS and is summarized in Figure 1.

Although it has been concluded that the complete research facility is required to meet all of the objectives of the Air Training Command, consideration has been given to a phased procurement that would start with certain equipments and incrementally build to a complete facility. Although there are many ways that this could be approached, there appear to be certain considerations that lead to a particular buildup plan. Although this plan indicates certain types of equipments, it should not be construed as a firm recommendation in all areas; however, the considerations that lead to this approach to the complete facility do merit consideration.

In Section 12 of this report, the complete facility recommended by Link is shown in Figure 56, and an approach to building one-half of the facility as a first increment is shown in Figure 57. It is also possible to approach the ultimate facility in smaller increments than those shown, and several possibilities will now be discussed. At the end of this section is a tabulation of the equipments that would result from the approaches discussed herein.

The smallest increment that appears to be worthy of consideration would be a single station (Station 1) with associated computer capability and instructor and experimentor stations necessary to enable some research to be performed. The T-37 cockpit would be the first to be procured, and the full visual system that is indicated would be desirable; however, if funding were limited, it would be possible to approach the visual system in two increments to minimize the initial cost.

Location	Equipment	Maneuvers with Visual Capability
Station 1	T-37 cockpit Six-degree-of-freedom motion system with G-seat General-purpose computer; complexity equivalent of one-half Sigma 5 Computer-generated visual image with wrap-around display Conventionally instrumented instructor control console Advanced instructor console Experimenter control console	Taxiing Takeoff Approach and landing Formation Airwork and aerobatics Night flying Instrument flying
Station 2	T-37 cockpit Six-degree-of-freedom motion system with G-seat General-purpose computer; complexity equivalent of one-half Sigma 5 Point-light-source visual display with wrap-around display Conventionally instrumented instructor's console and/or advanced instructor's console Experimenter control console	Airwork and aerobatics Instrument flying
Station 3	T-38 cockpit Six-degree-of-freedom motion system with G-seat General-purpose computer; complexity equivalent of one-half Sigma 5 Transparency or strip film visual system with wide-angle display Conventionally instrumented instructor's console and/or advanced instructor's console Experimenter control console	Navigation and low- level flight Instrument flying
Station 4	T-38 cockpit Six-degree-of-freedom motion system with G-seat General-purpose computer; complexity equivalent of one-half Sigma 5 CCTV/model or computed generated visual image with wide-angle display Conventionally instrumented instructor's console and/or advanced instructor's console Experimenter control console	Formation flying Instrument flying Might include: taxiing, takeoff, approach and landing, night flying, if computer generated visual is procured

Figure 1 RECOMMENDED UPTRSS EQUIPMENT COMPLEMENT AND SIMULATION CAPABILITIES

The next increment would be Station 2, which is a T-37 cockpit replica with the types of equipment tabulated in Figure 2. By procuring the second station, some economies would result in that only the simulation of a T-37 aircraft would be required and considerable research could be performed on the initial stages of the undergraduate pilot training curriculum. It is likely that the largest gains in the use of simulation equipments may be made in the initial phases of flight training in the T-37 aircraft.

The next increment would be Station 3, which would be a T-38 cockpit that would facilitate research in the areas of navigation and low-level flight. Again, the equipments associated with this cockpit are shown in Figure 2. Upon this increment, one would obviously require the math modeling and programming associated with the simulation of the T-38 aircraft.

The final increment would be Station 4 which would then complete the facility. The computational equipment and peripheral equipment would be procured in increments associated with each station until the final equipment complement is procured. No attempt has been made to detail the amount of memory and number of peripheral cabinets that would be procured with each increment, since there are a large number of variables that must be considered.

One other incremental buildup appears to be attractive from the standpoint of the visual system capability that results. This approach would be to procure Station 1 as in the first approach and then procure Station 3 as the next increment. This would permit research in most of the phases of flight since the Station 1 visual system can do a reasonable job of simulation in all flight phases except navigation and low-level flight, and the latter are provided by the visual system on Station 3. This approach would require the implementation of a T-38 aircraft simulation in the second increment, but would have the benefits of permitting research in both aircraft utilized in the undergraduate pilot training program. The equipments that would be included in each of the increments if this approach were to be adopted are also shown in Figure 2.

FACILITY INCREMENT	REPRESENTATIVE COMPUTER COMPLEXITY	VISUAL SYSTEM COMPLEMENT	MOTION SYSTEM COMPLEMENT	INSTRUCTOR/ OPERATOR CONSOLE	RESEARCH CONSOLE
Station 1	One Sigma 5 Computer	One T-37 simulator to be provided with a visual system of maximum versatility utilizing a digital electronic image generator and a segmented wraparound display as described in Section 9.6.1.	A six-degree-of freedom motion base plus G-seat	One console with conventional instrumentation, plus one console with advanced instrumentation such as CRT displays as outlined in Section 4.2.2.	One research console with capabilities as outlined in Section 4.2.1.
Stations 1 & 2	Two Sigma 5 Computers	Two T-37 simulators are required, one having the visual system described for Station 1 and the other with the point-light-source projection visual display delineated in Section 9.6.3. Station 2 especially intended for airwork and aerobatic training and associated study.	Two six-degree-of-freedom motion systems plus G-seats; one for each simulator.	Same as above for each station.	Two research consoles. one for each simulator, in a centralized location as described in Section 4.2 and 4.2.1.
Stations 1 & 3	Two Sigma 5 Computers	Station 1 as described above. Station 3 utilizes a T-38 cockpit with a navigation and low level flight visual simulation capability utilizing either a strip film projection or a transparency reconstruction system as delineated in Section 9.6.2.	Same as above.	Same as above for each station.	Same as above.
Complete Facility	Three Sigma 5 Computers	The complete facility incorporates Stations 1, 2, and 3, outlined above, plus Station No. 4, which provides the second T-38 simulator with a scale-model/CCTV or an electronically generated image for formation flight training as described in Section 9.6.4.	Four six-degree-of-freedom motion systems plus G-seats; one for each	Same as above for each station.	Four consoles, one for each simulator.

Figure 2 INCREMENTAL APPROACHES TO FACILITY PROCUREMENT

2. CREW STATION REQUIREMENTS

2.1 CREW FACILITIES

The crew facility definitions presented in this section of the report are the result of long study and much discussion between Link and Air Force representatives. The resulting recommendations are that four crew compartments should be provided, two of the T-37 type and two of the T-38 type. The extent of simulation of instruments and controls in each cockpit type should be determined by the utility of such equipment to the training task.

For the T-38 cockpit it is recommended that only the front seat cockpit be simulated, since, unlike the T-37, there is little visual contact between the instructor and student and the student cannot see the instructor's cockpit. The rear seat (instructor's cockpit), if simulated, could be instrumented with training evaluation equipment (see Section 4). It is extremely difficult to provide an adequate visual scene simulation to both instructor and pilot, and priority should be given to providing the student pilot with the most realistic environment.

A similar visual simulation criterion should apply to the T-37 cockpit. However, in this case it is felt that since the instructor/student communication is more direct, the absence of the instructor would seriously detract from the true environment. Since the pilot must refer to the right-hand side of the instrument panel, a simulation of the entire cockpit is necessary. Further details are considered in Section 2.2.2.

Figure 3 is a view of the T-4 trainer cockpit, similar to the T-37. It shows that there is little room for trainee evaluation equipment in the T-37 cockpit that would not be in the direct view of the trainee; however, with certain hardware restrictions some additional equipment can be implemented (see Section 4 for discussion).

Figure 4 and 5 show forward and rear cockpit configurations of the T-38.

2.2 COCKPIT CONFIGURATION

2.2.1 Extent of Simulation

The extent of true simulation of equipment in the crew compartment (such as ejection seat, map storage, fire extinguisher, etc.) should be decided by studies of its impact on the trainee learning process. If after study it is apparent that the item has no impact on the trainee learning process, then a comparatively crude mockup will be satisfactory. If, however, the item is part of a standard training procedure (for example, controls used during the procedure for ejection) then a full and operable simulation may

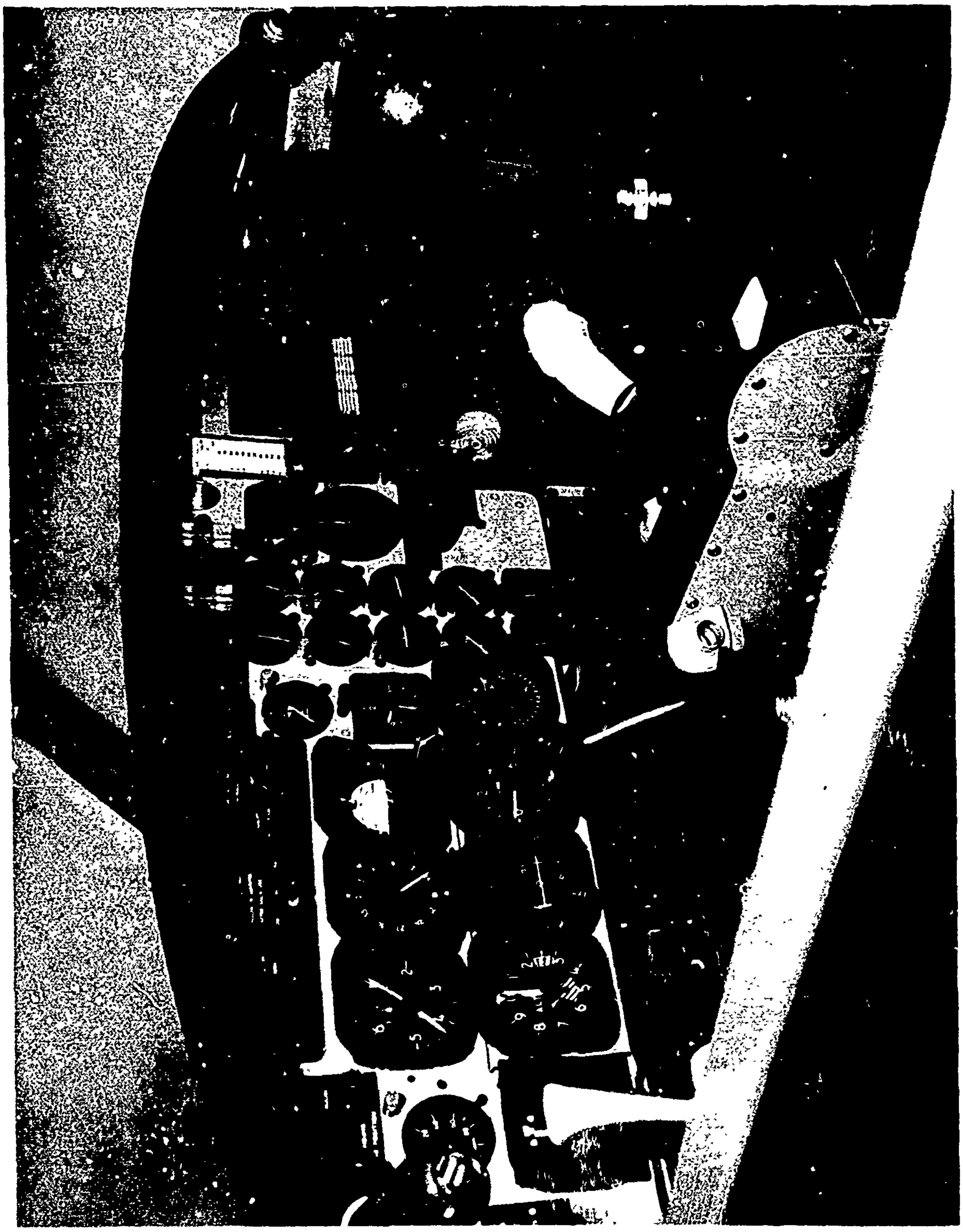


Figure 3 T-37B CREW COMPARTMENT

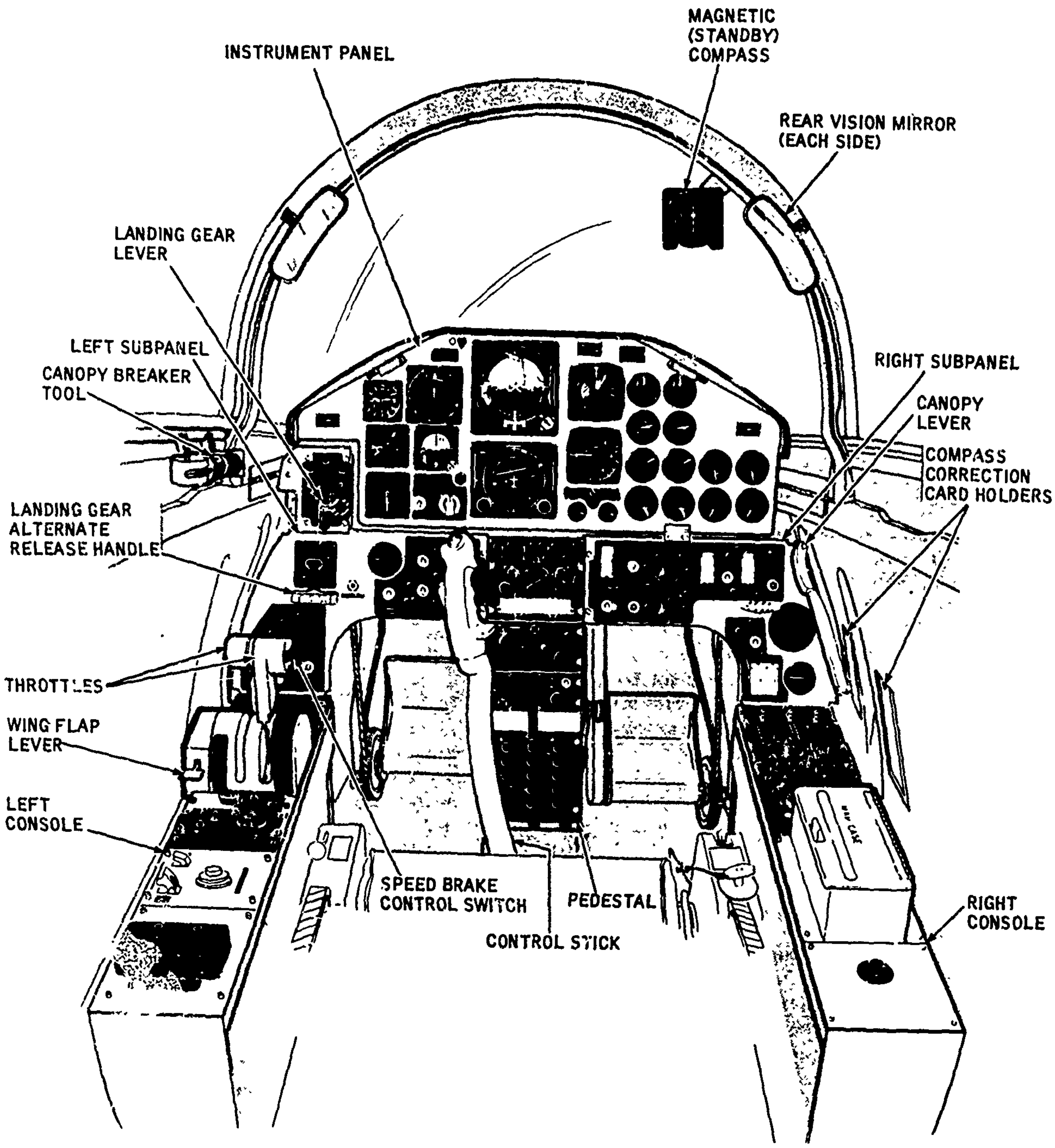


Figure 4 T-38A FRONT COCKPIT

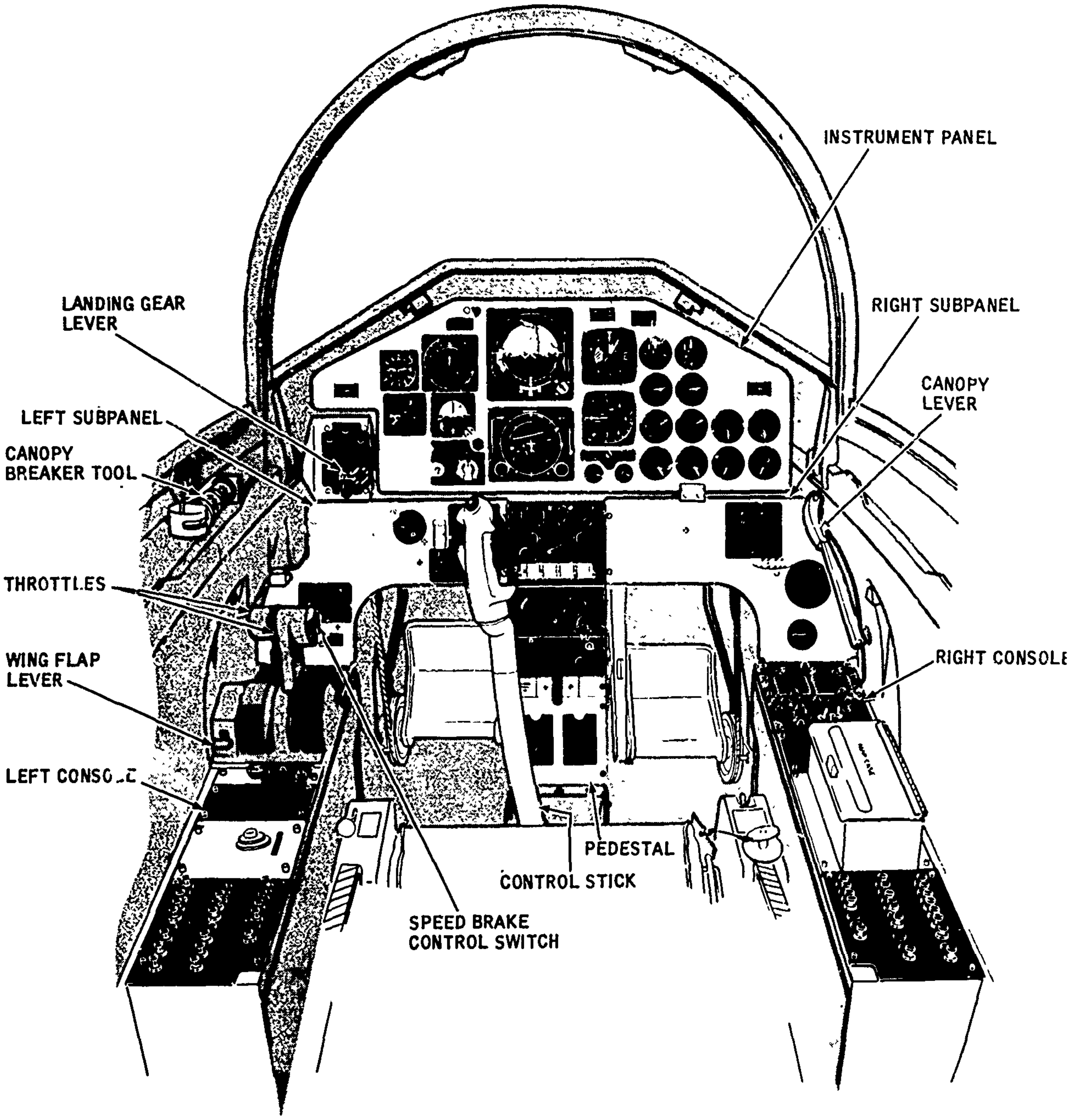


Figure 5 T-38A REAR COCKPIT

appear desirable. The ground rule should be that in all cases where an element of doubt exists, the item should be provided as a full simulation in order that the research facility may evaluate its utility.

One consideration which may cause the research facility crew station to differ from Figures 3 or 4 is the requirement to progressively degrade the fidelity of the indications (and perhaps the response to control movements) for research purposes. The crew station design should permit the covering of certain instruments for experimental purposes (see Section 3). In the event that the facility may be required to investigate the substitution of simulated or less accurate instruments for the installed high-fidelity instruments, a modular panel construction system, which would enable individual instruments to be moved and replaced, would seem desirable.

The "fidelity" of simulation of instrument indications can also be varied by changes in the simulator computer programs. The change in fidelity due to changes in the software simulation model are discussed in greater detail in Section 3 of this report.

2.2.2 Instructor/Trainee Provisions

The immediate area of the pilot trainee station has a profound effect on the realism of the training program. High fidelity of the canopy sill, windshield arch, and visibility angles would seem to be important requirements, with dimensional accuracy, texture, and other detail becoming less important as the frequency of manual or visual reference to it decreases. The use of fiberglass molded parts for canopies and windshields has been recommended almost exclusively in recent years. Lighting techniques minimize the effect of the substitution of thin plastic panels to replace the thick and heavy glass of the aircraft. Minor deviations from aircraft lines, generally not discernible to a trainee, are employed to simplify the molded parts and eliminate compound curvature in the mating parts. The most economical approach to the structure below the sill line is a steel weldment with framework spaced as open as possible to provide maximum access when covers are removed.

The construction of the cockpit should be compatible with a motion system utilizing a platform for actuator attachments in which the actuators do not impose loads on the cockpit other than accelerations of ±3g. Similarly, the visual system should be independently mounted to the motion platform (see Section 8) and not necessarily rely on the cockpit for stability. Indeed, a concept for the Farrand "pancake window" (Section 9) visual system involves withdrawal of the cockpit along tracks from the visual complex to permit entry to the trainee station. This is reflected in Figure 56 in the form of support structure at the rear motion platform. The study of cockpits suitable for this type of training resulted in a selection of two types, one with a side-by-side seating arrangement as in the T-37 aircraft and the

other a tandem, T-38-style cockpit. The T-37 offers the advantage of providing an optimum location for direct observation of the trainee's actions from the righthand seat. Tandem seating for an instructor is of questionable value in a simulator, and may be replaced with a jump-seat station that will serve primarily as a position from which preliminary orientation training can be conducted, or, as stated in Section 2.1, as an additional station for trainee evaluation.

Ingress and egress to and from the cockpits has always been stressed as a critical factor in enhancing the realism of training, and should be maintained as closely as possible to that of the aircraft.

The selection of loading devices to duplicate the forces, travel, and feel of the aircraft controls should be those most appropriate for the controls being simulated and those which have survived the trials of time — i.e., are known to have a high reliability. The hydraulic control loading devices should reflect the latest product improvements. Loading, feel, and response characteristics of such devices should be capable of being varied over a wide range, permitting evaluation of various characteristics for research purposes.

2.2.3 Location of Crew Stations

The suggested location for the crew stations of the T-37 and T-38 simulators with respect to the other modules comprising the research facility is shown in Figures 56 to 58 and was developed from many considerations to be discussed in this study, including the following factors:

1) The requirement that the crew compartment and associated instructor stations be in close proximity to one another.

2) The requirement that the research station be in close proximity to the crew compartment and instructor station.

3) The requirement for the shortest possible distance between the computer and computer interface and the crew compartments.

4) The requirement for the shortest possible distance between any visual image computing system and the crew stations.

5) The need to provide adequate space for crew compartment motion systems.

6) The need to provide adequate space for crew compartment visual systems.

7) The requirement for easy entry to and exit from the crew stations, under both normal and emergency conditions.

8) The provision of adequate research equipment workspace, and conference rooms.

The suggested layout situates the crew compartments in the four corners of a building approximately 88 ft. square. The crew compartments therefore surround a central area which is envisaged as two levels, with all computer, interface, and peripheral equipment located on the lower level, and the upper level containing research and operator consoles. The upper level height above the floor level will be the same as the settled height of the crew compartment motion systems. Access to the crew compartment(s) will therefore be directly from the upper level by means of sliding or folding ramps.

2.3 COCKPIT MOTION

The outcome of the study discussed in detail in Section 8 is a requirement for a six-degree-of-freedom motion capability for both T-37 and T-38 aircraft. This approach is essential if the research facility program is to examine the transfer of training with six or fewer degrees of freedom, and with changes in the fidelity of motion simulation, as they relate to each of the important training phases. This should enable an optimization of equipments and software for each of the training phases. As Section 9 shows, the number of cockpits is primarily dictated by the visual system requirements. Four six-degree-of-freedom systems are recommended, (two T-37's and two T-38's) and Figure 56 shows an example of the facility configuration having four Link standard six-degree-of-freedom systems. This is illustrated as a typical example of a current state-of-the-art equipment and is not a specific recommendation. The excursion requirements relating to the six-degree-of-freedom simulation of the T-37 and T-38 aircraft are discussed in Section 8, and will affect the final size of the facility.

Another recommendation resulting from the study, is to provide, for all four cockpits, the capability of sustained acceleration simulation. This is best accomplished by utilizing a "G"-seat device. (The details of such devices are discussed in Section 8). In the implementation of such devices it is important to ensure that the equipment is not unwieldy and does not detract from creating a good simulation of the cockpit environment.

Considerable attention must be given to safety considerations. Section 8 reviews in detail recommendations for safety and operation of motion system and "G"-seat devices.

2.4 VISUAL SYSTEM PROVISIONS

An important requirement for the crew stations is to provide an adequate simulation of the visual environment presented to the pilots of T-37 and T-38 aircraft. There is undoubtedly considerable training value associated

with the simulation of visual scenes as they relate to each of the maneuvers of the curriculum discussed in the introduction. Unfortunately no state-of-the-art visual system presently available is capable of providing real-world fidelity for any maneuver, and thus compromises must be made. Section 9 of this report discusses these compromises as they relate to the undergraduate pilot training problem.

Based upon the conclusions drawn in Section 9, four visual systems are defined:

1) Wide-angle computer-generated display on T-37 cockpit, for takeoff and approach and landing training, with the general capability for conducting research in all other phases of training

2) Wide-angle point-light-source display on T-37 for airwork and aerobatic training, with experimental capability involving relatively low-quality images

3) Moderate-field-of-view display on T-38 utilizing computer-generated display for formation flight training and study or using motion picture projector for takeoff and landing training and study

4) Wide-angle display on T-38 cockpit utilizing a transparency reconstruction system for navigation and low-level flight simulation for training and for study

As discussed in Section 9, these four systems are considered the most practical state-of-the-art combinations for simulators capable of fulfilling both the training and research requirements of the UPTRSS.

2.5 EXPANDABILITY AND ADAPTABILITY

A requirement of the UPTRSS is that it possess flexibility and adaptability for the modification of software and hardware so that changes in training device technology, changes in research requirements, changes in operational equipment being simulated, and changes required as a result of research can be readily incorporated.

It is highly desirable that UPTRSS modifications be carried out as far as possible without interrupting training and research time. The availability of four separate cockpits goes a long way toward fulfilling this objective.

Provision for changes (e.g., adding routines such as for advanced training research) which increase the simulation task can be accommodated by making the provision for extra computing time and memory in the simulator complex. This growth provision will also permit simulation of future

aircraft systems, and will also allow for additions to the visual scene (such as programming for special effects projectors) and for new simulation requirements that cannot be specifically defined at this time. Careful consideration has been given to these factors in sizing the computer complex and peripheral facilities (see Section 5).

In the event that the research facility is built in a series of phases, it is desirable that the overall design be evolved in a manner which permits a working series of modules (research console, instructor console, computer, and crew compartment) to be assembled and commissioned at the earliest possible moment. It is important that during the progressive addition of a research facility modules, the ability to continue research on those modules already installed be disturbed as little as possible. This concept is reflected in the alternate facility considerations (see Section 12.2.3).

3. COMPLEXITY OF AIRCRAFT SIMULATION

3.1 COCKPIT INSTRUMENTATION

As stated in Section 2, the ground rule for both T-37 and T-38 cockpit simulators should be to provide full cockpit instrumentation until and unless it is verified that certain assemblies do not contribute significantly to training. The capability for changing or covering instrumentation display is desirable and has been discussed in Section 2. An alternative approach is to provide degradation in the fidelity of the instrument reading by changes in the software programs that drive these instruments. The study philosophy evolved recommends that a so-called "high fidelity" math model be developed which can be progressively degraded and would thus provide a varying degree of training difficulty. This is discussed in detail in the following sections.

3.2 PERFORMANCE OF SIMULATED AIRCRAFT

The contrast between the UPTRSS performance requirement and typical nonresearch simulator performance requirements lies simply in those training facets which may have been compromised or omitted, although they could be of significant training value. These facets should not be subject to compromise or omission within the research simulator. There are only a few such areas which have been subject to compromise within the nonresearch simulators due primarily to lack of data in these phases (i.e., stall, spin, jet wakes and downwash areas) and, in general, the nonresearch simulators are designed to MIL-T-9212B requirements. These simulators represent the current state of the art with respect to performance of the simulated aircraft. UPTRSS simulators should employ as their high-fidelity simulation, or most complex level of simulation, present state-of-the-art developments which fulfill MIL-T-9212B; in addition, in those areas where compromises have previously been made, the UPTRSS simulators should be supplied with appropriate software.

This software should form the high-fidelity simulation package from which all experimentation in performance degradation begins. This package should also provide the standard against which the results of degradation can be compared.

3.2.1 Tolerances

As mentioned earlier, the UPTRSS simulator tolerances should be those specified by MIL-T-9212B. These tolerances are within the current state of the art of software design and should be met by the high-fidelity simulation package. In certain of the cases below the tolerance level has been changed to what is felt to be a more realistic value given

within the F-4E specification. Exhibit SEMT 66-104. Parameters affected by this change carry an asterisk thereafter.

3.2.1.1 General Tolerances

Performance, stability, and control of any aircraft or aircraft equipment which is not covered by a specific tolerance listed herein should be in accordance with design criteria, with the following listed general tolerances applicable to the individual parameters involved. Tolerances should be applicable either to the dependent or the independent variable of a particular curve.

Individual force along any axis	2%, or 0.2% of maximum value
Individual moment about any axis	3%, or 0.3% of maximum value
Total mass	1%
Moments of inertia	1%, or 0.1% of maximum value
Angular accelerations	5%
Linear accelerations	5%

3.2.1.2 Curve Slope

In addition to the tolerances specified herein and in the detail specification, the shape of any curve of trainer performance should be similar to that of the design criteria. The sign of the second derivative of any section of the trainer performance curve and the design criteria should be the same. Where a section of a curve is represented by a series of straight lines, the sign of the second derivative should be implied by the trend of slope change of succeeding segments. Where a section of a curve obtained from design criteria and a trainer performance curve are linear and continuous, the slope of the two curves at the same X value should be the same ±10°. Prior to comparing the curve slopes, they may be translated in X and Y to obtain the best fit, provided no point of the trainer performance curve falls outside the tolerance boundaries of the design criteria curve before or after translation. The comparison of curves should be permitted only when the trainer curve and the design criteria curve are at the same scale.

3.2.1.3 Powerplant Tolerances

Those tolerances which are not directly applicable to the UPTRSS T-37 and T-38 simulators are noted with a dagger (†). The power tolerances should be as follows:

Power lever position	2% above 75% power, 5% below 75% power, or 0.5% of maximum value
Fuel flow	5%, or 0.5% of maximum value
Fuel flow rate of change	25%
Fuel depletion rate	5%, or 0.3% of maximum value
Fuel pressure	10%, or 0.1% of maximum value
Fuel pressure rate of change	25%
Fuel temperature	5%
Fuel temperature rate of change	25%
Engine rpm	±2%
Engine acceleration	10%
Engine windmilling speed	5%
Idle governing engine speed	2%
Exhaust gas temperature	3% from idle to 75% power, 1.5% above 75% power
Exhaust gas temperature rate of change	25%
Oil pressure	5%
Oil pressure rate of change	25%
Oil temperature	10%, or 5% of maximum value
Oil temperature rate of change	25%
Turbine inlet air temperature	5°
Turbine inlet air temperature rate of change	25%
Pressure ratio	2% below cruise, 1% cruise and above
Pressure ratio rate of change	25%
Thrust	2%, or 0.2% of maximum value

Torque pressure		300 in-lb
Torque pressure rate of change		25%
Shaft horsepower at normal cruise and takeoff power setting	†	20 bhp, (elsewhere 50 bhp)
Engine vibration		20%

3.2.1.4 Aerodynamic Tolerances

The aerodynamic tolerances should be as follows:

True airspeed vs indicated airspeed	*	0.5% of maximum value or 2.5 knots
Indicated mach number vs true airspeed		2%, or 0.5% of maximum value
Critical speed indicator		2 knots
Surface deflection vs control deflection		5% from 0° to 10°, 0.5° from 10° to maximum control deflection
Control force vs control deflection		5%, or 1% of maximum value
Surface deflection vs constant pitch, roll, and yaw rates individually		5%, or 1% of maximum surface deflection
Surface deflection vs pitch, roll, and yaw accelerations individually		5%, or 1% of maximum surface deflection
Static longitudinal stability (surface deflection vs constant pitch attitude)		5%, or 1% of maximum surface deflection
Static lateral directional stability (surface deflection vs constant yaw angle)		5%, or 1% of maximum aileron surface deflection; 5%, or 1% of maximum rudder surface deflection
Dynamic stability:		
Amplitude	*	±10%
Period	*	±10% or 0.25 seconds

Damping coefficient	*	±10%
Low frequency gain:		
At any one condition		5%
Subsidence ratio or percentage of overshoot		5%
Takeoff:		
Attitude	*	±1°
Airspeed		2 knots
Time to takeoff speed	*	±2 seconds
Maximum airspeed (zero climb)		1%
Stopping time		10%
Dynamic pressure		3%
Rate of climb		5%, or 50 feet per minute

3.2.1.5 <u>Navigation Tolerances</u>

The navigation tolerances should be as follows:

Course recorder position counters	0.5 mile
Cross-country/approach recorder track	(Wind zero) 1° (With wind) 2°
Cross-country/approach recorder ground distance	(Wind zero) 2% (With wind) 3%
Relative bearing	2°
Localizer beam location	30 feet
Localizer beam approach bearing	1°
Glidepath beam location	10 feet
Glidepath beam angle	6 minutes of arc

Gyro precession rate	25%, or 2° per hour
Turn rate	2%
Climb rate - (Altitude change/ time vs rate of climb indicated)	10%, or 20 feet per minute
Magnetic variation	2°
Altitude recorder:	
Altitude deviation	0.5%
Absolute altitude	10 feet, or 0.5%
Distance	1%
Field elevation	10 feet
Signal attenuation vs distance	25% signal strength
Radio beam width	20%
Distance indicator	0.5%
Radio marker location	0.1 mile
Glideslope deviation recorder	5 feet

3.2.1.6 Duplicate Instrument Tolerances

The maximum deviation of the duplicate instrument indications from the flight compartment instrument indications should be as follows:

Altitude	20 feet
Heading	1°
Indicated airspeed	2%
Rate of climb	2.5%, or 10 feet per minute
Attitude:	
Pitch	0.25 bar width, or 20%
Bank	1%

Turn and bank indicator:	
Turn needle	1/8 needle width, or 12.5%
Skid indicator	1/8 ball diameter, or 12.5%
Accelerometer	0.1g
Exhaust gas temperature	1°
Turbine inlet temperature	1°
Engine speed	0.5%
Machmeter	0.005
Fuel level	1° rotational
Tachometer	0.5%
Fuel flow	50 pounds per hour
Oil pressure	2 pounds per square inch
Oil temperature	4°
Percent thrust	0.5%
Outside air temperature	1°
Engine pressure ratio	.002 ratio
Others	2° rotational, or 1% of maximum

3.2.1.7 System Tolerances

Unless otherwise specified, system tolerances should be as follows:

Fuel transfer rate	20%
Hydraulic pressure	3%
Hydraulic pressure rate and hydraulic system operating capacity	25%

Voltage	1%
Loadmeter and ammeter	5%
Power (electrical)	5%
Electrical device load	5%
Oil quantity	20%
Oil transfer rate	20%
Water quantity rate	† 25%
Water quantity (maximum)	† 10%
De-ice cycling rate	5%
Surface and duct temperature	8%, or 5% of maximum
Cabin altitude	100 feet
Extension, retraction times	1 second
General time delay (switch to light warm up)	10%
Control force vs control deflection (throttles, nose steering)	10%
Pneumatic pressure	3%
Pneumatic pressure rate	25%
Pneumatic system operating capacity	25%
Trim system response rate	10%
Landing and cowl flap limiting position	2%
Actuator response time	1 second
Altimeter at landing	20 feet
Standby compass	3°

Free air temperature	2°
Accelerometer	0.1g
Bleed air pressure	5%
Rate of change of cabin altitude	20 feet per minute, or 10%
Propeller feathering time	† 2 seconds

3.2.2 Post-Stall and Spin Simulation

In both deep-stall and spin conditions, the aerodynamic coefficients which describe the forces and moments acting upon an aircraft differ greatly from those which apply to normal flight conditions. Angle of attack and sideslip angle both may vary as much as ±90°. Under normal flight conditions the lateral-directional coefficients are not seriously affected by angle of attack and pitching, and the pitch plane coefficients are not seriously affected by sideslip angle and yaw-roll rates. Also, linear approximations to angle of attack and sideslip contributions are usually employed.

The equations of motion which are currently employed in flight simulators are capable of handling both post-stall and spin conditions if the applicable aerodynamic coefficients can be generated. In most operational flight simulators a rigorous simulation has not been attempted because either coefficient data in post-stall and spin conditions has not been available for the simulated aircraft or the size of the computational task makes it undesirable. General practice has been to sense the conditions when the simulator should spin or stall, and then introduce indications of a deep stall or spin. If the pilot applies the correct recovery procedure, then the simulator appears to recover properly and reverts back to normal computation.

According to Cessna, there are no post-stall and spin aerodynamic coefficient data available for the T-37 aircraft; there is, however, a great deal of information available about the deep-stall and spin of the aircraft. Norair has simulated both deep-stall and spin of the T-38 aircraft, and aerodynamic coefficient data are available for the T-38. Student pilots are allowed to practice spinning the T-37 aircraft, but not the T-38. They are taught T-38 spin recovery procedures, but do not practice spins. Therefore it appears that if a high-fidelity spin simulation were desirable, it could be simulated for the T-37; however, since aerodynamic coefficient data in deep-stall or spin are not available for the T-37, it appears that the type of simulation which is currently employed in operational flight simulators would be in order for both T-37 and T-38 simulations. That simulation is such that entry, stall, and spin indications, and the recovery, appear correct to the pilot, but post-stall and post-spin aerodynamic coefficients are not generated. Since it is possible to stall or spin by improper control during any phase of flight, spin and deep-stall should be simulated for all cockpits.

The type of deep-stall and spin simulation recommended is of such low complexity that the problem of degradation does not arise. It is possible, however, to allow the normal flight coefficients to carry over into the deep-stall and spin regimes and accept whatever response falls out. This could have a negative training effect, but it might be acceptable for cockpits associated with training phases in which deep stalls and spins should not be encountered.

3.3 FLIGHT AND ENGINE SIMULATION

3.3.1 Flight Simulation

3.3.1.1 Equations of Motion

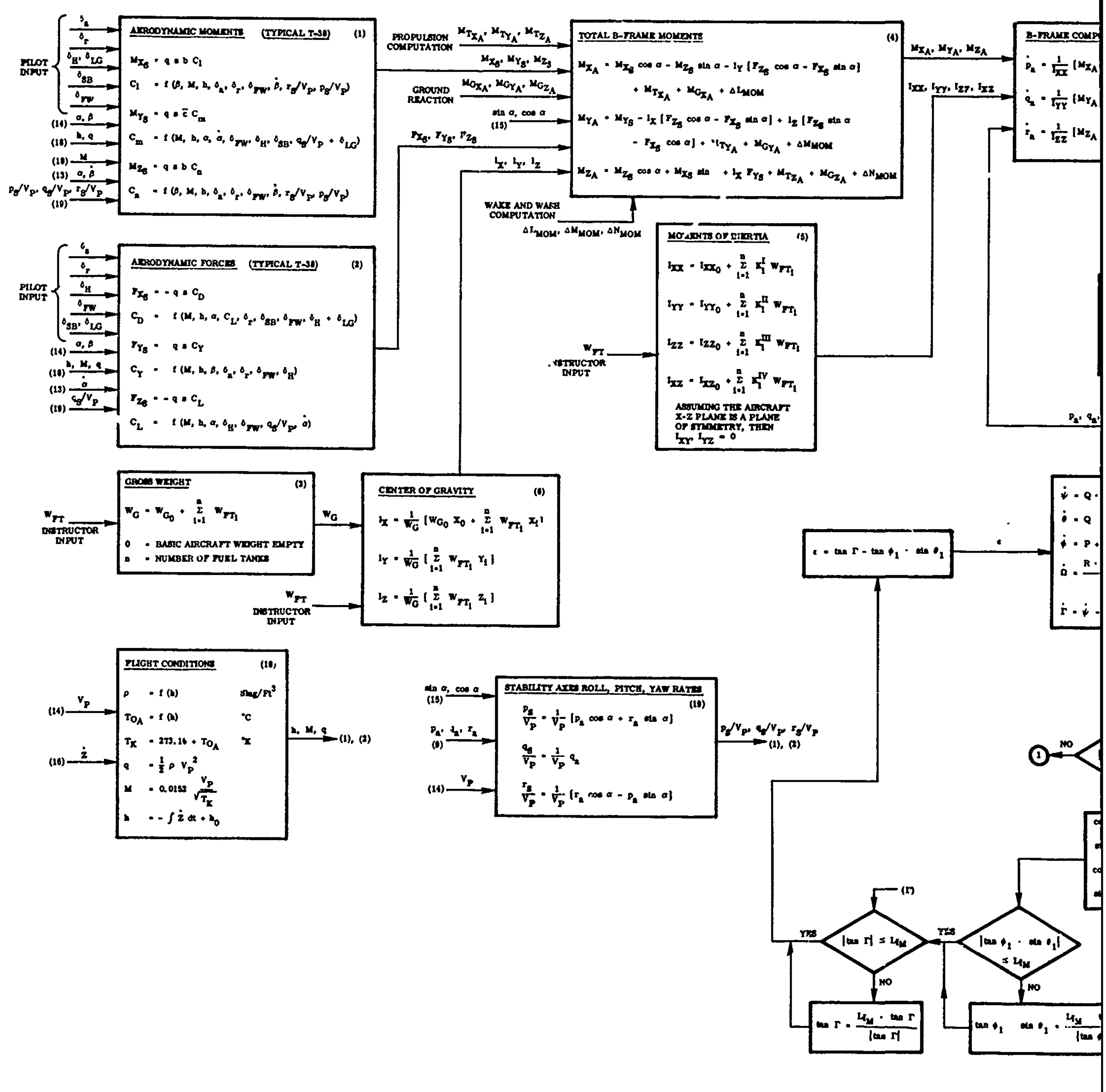
The equations of motion shown if Figure 6 are the recommended approach to high-fidelity simulation of the six degrees of freedom of aricraft flight. The translational velocity components and the rotational accelerations are computed by application of Newton's laws to functions of applied forces, moments, and mass properties.

The orientation of the coordinate system is computed by the use of an extended Euler angle system. This system was developed in an effort to find a reasonable compromise between the requirements for convenient outputs for cockpit display and suitable accuracy at all attitudes. The extended Euler angle system, as defined by D. T. Greenwood of the University of Michigan, uses ordinary Euler angles plus an additional angle measured in the horizontal plane, The additional coordinate aids in two principal ways. First, it provides a redundancy that can be used for error-correcting purposes. Second, it is well-behaved at near-vertical attitudes and thereby prevents attitude indeterminacy. Note that the correcting signal goes to zero for vertical flight where the rate of the fourth angle ($\dot{\lambda}$) is well behaved but corrects $\dot{\lambda}$ most strongly for pitch equals zero where λ is more likely to be in error. A similar consideration indicates that the correcting signal will be maximum for vertical flight where the calculation of the yaw rate is least accurate. On the other hand, the correcting signal will go to zero for horizontal flight where the yaw rate calculation is most accurate.

In the neighborhood of vertical flight the pitch angle is frozen — i.e., set equal to a constant which is a function of the computer word size. Likewise, when pitch equals zero and roll equals 90°, the calculation of $\dot{\lambda}$ is indeterminate and similarly the roll angle is set equal to a constant in the neighborhood of 90°.

3.3.1.2 Aerodynamic Equations

The aerodynamic characteristics are defined by the six aerodynamic coefficient equations. Aerodynamic coefficients reflect the aircraft configuration and flight condition as functions of landing gear,


AERODYNAMIC MOMENTS (TYPICAL T-38) (1)
PILOT INPUT
PROPULSION COMPUTATION
GROUND REACTION
TOTAL B-FRAME MOMENTS (4)
B-FRAME COMP
WAKE AND WASH COMPUTATION
MOMENTS OF INERTIA (5)
ASSUMING THE AIRCRAFT X-Z PLANE IS A PLANE OF SYMMETRY, THEN
AERODYNAMIC FORCES (TYPICAL T-38) (2)
INSTRUCTOR INPUT
GROSS WEIGHT (3)
BASIC AIRCRAFT WEIGHT EMPTY
NUMBER OF FUEL TANKS
CENTER OF GRAVITY (6)
FLIGHT CONDITIONS (18)
STABILITY AXES ROLL, PITCH, YAW RATES (19)
YES
NO

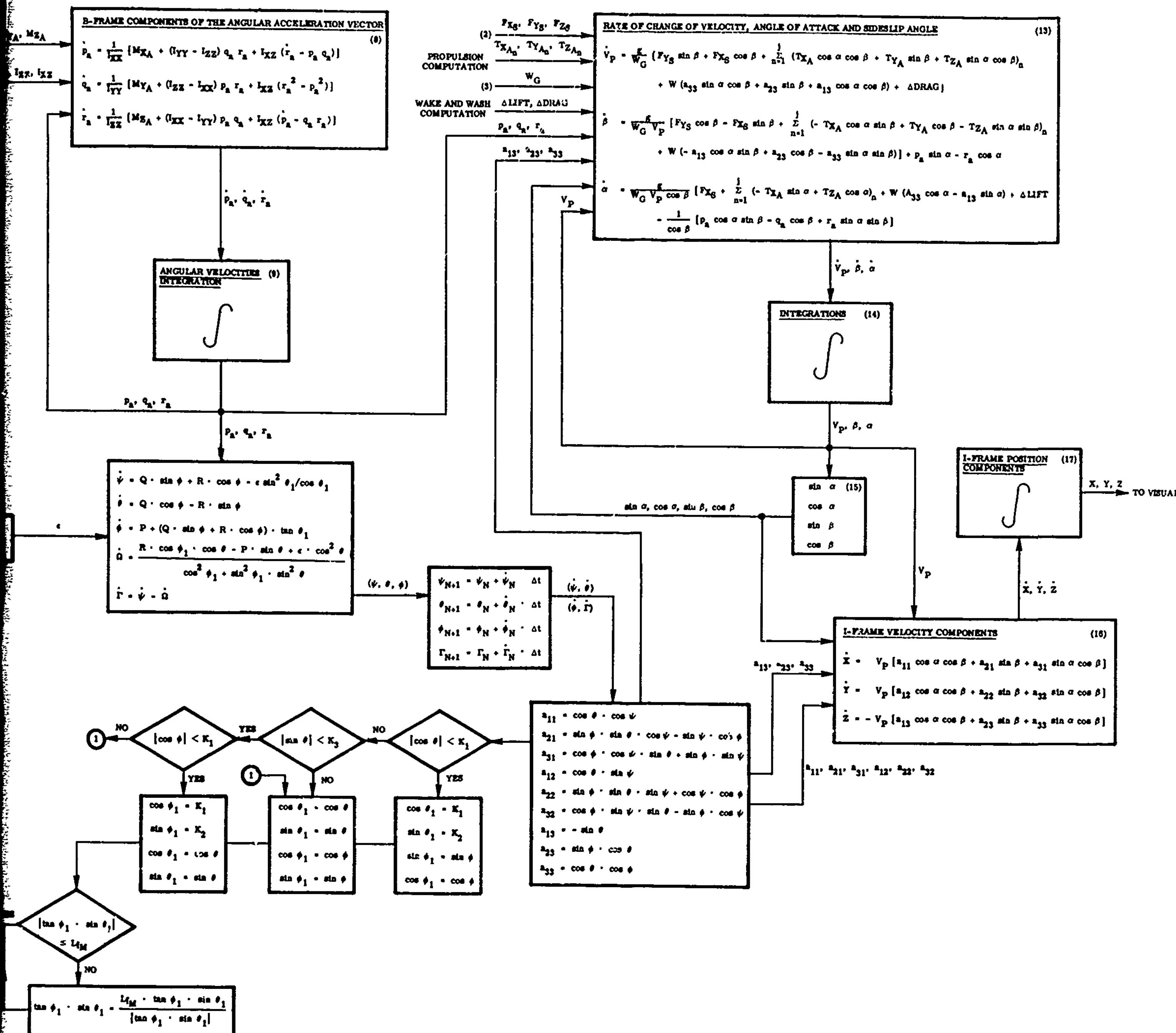


Figure 6 HIGH-FIDELITY SIMULATOR FLIGHT COMPUTATION SYSTEM

B,

flaps, Mach number, altitude, angles of attack and sideslip, and pilot input of the control surfaces.

The aerodynamic coefficients, and consequently the forces and moments which they produce, are defined in the stability axis system. To be used in the equations of motion, the aerodynamic force and moment equations are transferred to the wind axes and body axes respectively. Similarly, the body axis angular rates must be transformed into the stability axes to be used in the coefficient equations.

3.3.1.3 Weight and Balance

The gross weight, moments of inertia, and center of gravity location of the simulated aircraft should be continuously computed to provide instantaneous mass data to the equations of motion. Since the aircraft's X-Z plane is considered to be a plane of symmetry, the products of inertia I_{XY} and I_{YZ} are negligible and only I_{XZ} term should be computed.

The moments of inertia are computed by applying the parallel axis theorem so that the moments of inertia of the individual components are transferred to a common point and then added.

3.3.1.4 Ground Reaction Computations

The motion of the simulated aircraft is influenced by the forces and moments caused by compression of the landing gear struts and friction due to the rolling or skidding wheels when the landing gear is in contact with the ground. Deflections of the struts are determined from the altitude of the aircraft center of gravity and the pitch and roll attitude of the aircraft with respect to the ground plane. The force produced by each strut is a function of the deflection and deflection rate of the strut. The maximum friction force possible at each wheel is a function of the strut force and the coefficient of friction. Braking friction simulation is obtained as a function of strut force and pedal deflection.

Nose wheel steering is kinematically simulated as a function of the nose wheel angle, velocity, and geometry of the landing gear. If nose wheel steering is disengaged, the nose wheel angle will decrease to zero and thereby simulate nose wheel castering.

3.3.1.5 Degradation of the Fidelity of Flight Simulation

It is possible to degrade the motion, aerodynamic force and moment, weight and balance, and ground reaction equations in a number of different ways and still maintain a certain degree of simulation required for pilot training. However, the degree of degradation is dependent on the tolerance specification provided for the simulation of a particular aircraft.

Figures 7 and 8 illustrate two possible degrees of degradation of the aerodynamic force and moment equations and the equations of motion. Degradation of the weight and balance equations is not illustrated. The aerodynamic coefficient equations have been simplified such that only the basic flight conditions are utilized. The equations of motion have been degraded by assuming small-angle approximations. The philosophy of the small angle approximations is simply that the sine of a small angle is approximately equal to the angle itself measured in radians, the cosine of a small angle is approximately unity, and the product of the sine of a small angle and the square of its sine is negligible. Further, it is assumed that the body-axes angular rates are small (less than unity) in normal flight. It is possible then to neglect the squares and products of these terms. Figure 7 shows an intermediate complexity level where only the small-angle approximation concept is used.

It is possible to degrade the weight and balance simulation such that only two or three gross weights, centers of gravity, and moments of inertia corresponding to the specified weights are constants. These quantities could be instructor inputs.

The simulation of the ground reaction equations of motion can be degraded in various ways. Some possibilities considered are as follows:

1) Nose wheel steering could be accomplished by computing a rate of turn on the ground as a function of rudder input to the yawing moment equation and the effect of individual pedal deflection.

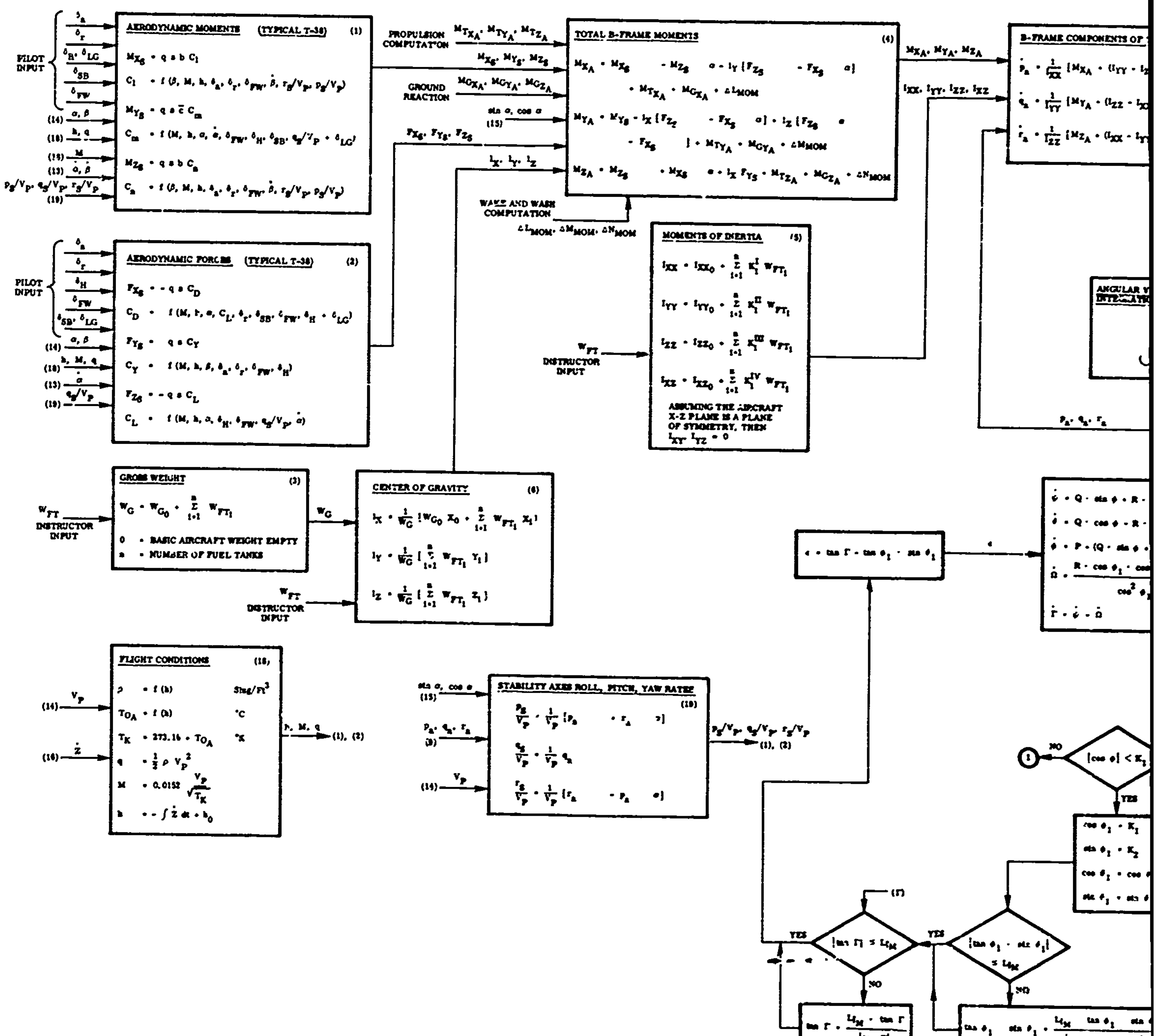
2) The simulation of a castering nose wheel can be eliminated.

3) Braking friction can be made constant.

The amount of degradation of the equations describing aircraft flight as well as ground operation is, as stated before, dependent on pilot training and tolerance specification. The schemes stated in this section are only some suggested possibilities.

The symbols used in Figures 6, 7, and 8 are defined as follows:

α	Aerodynamic angle of attack, defined to be the angle between the X_A axis and the projection of the V_P vector on the aircraft plane of symmetry (deg)
$a_{11} \cdot \cdot a_{33}$	B-frame to I-frame direction cosines (dimensionless)



PILOT INPUT
AERODYNAMIC MOMENTS (TYPICAL T-38) (1)
PROPULSION COMPUTATION
GROUND REACTION
TOTAL B-FRAME MOMENTS (4)
B-FRAME COMPONENTS OF
WAKE AND WASH COMPUTATION
AERODYNAMIC FORCES (TYPICAL T-38) (2)
MOMENTS OF INERTIA (5)
DISTRUCTOR INPUT
ASSUMING THE AIRCRAFT X-Z PLANE IS A PLANE OF SYMMETRY, THEN
GROSS WEIGHT (3)
BASIC AIRCRAFT WEIGHT EMPTY
NUMBER OF FUEL TANKS
CENTER OF GRAVITY (6)
FLIGHT CONDITIONS (18)
STABILITY AXES ROLL, PITCH, YAW RATES (19)
YES
NO

A,

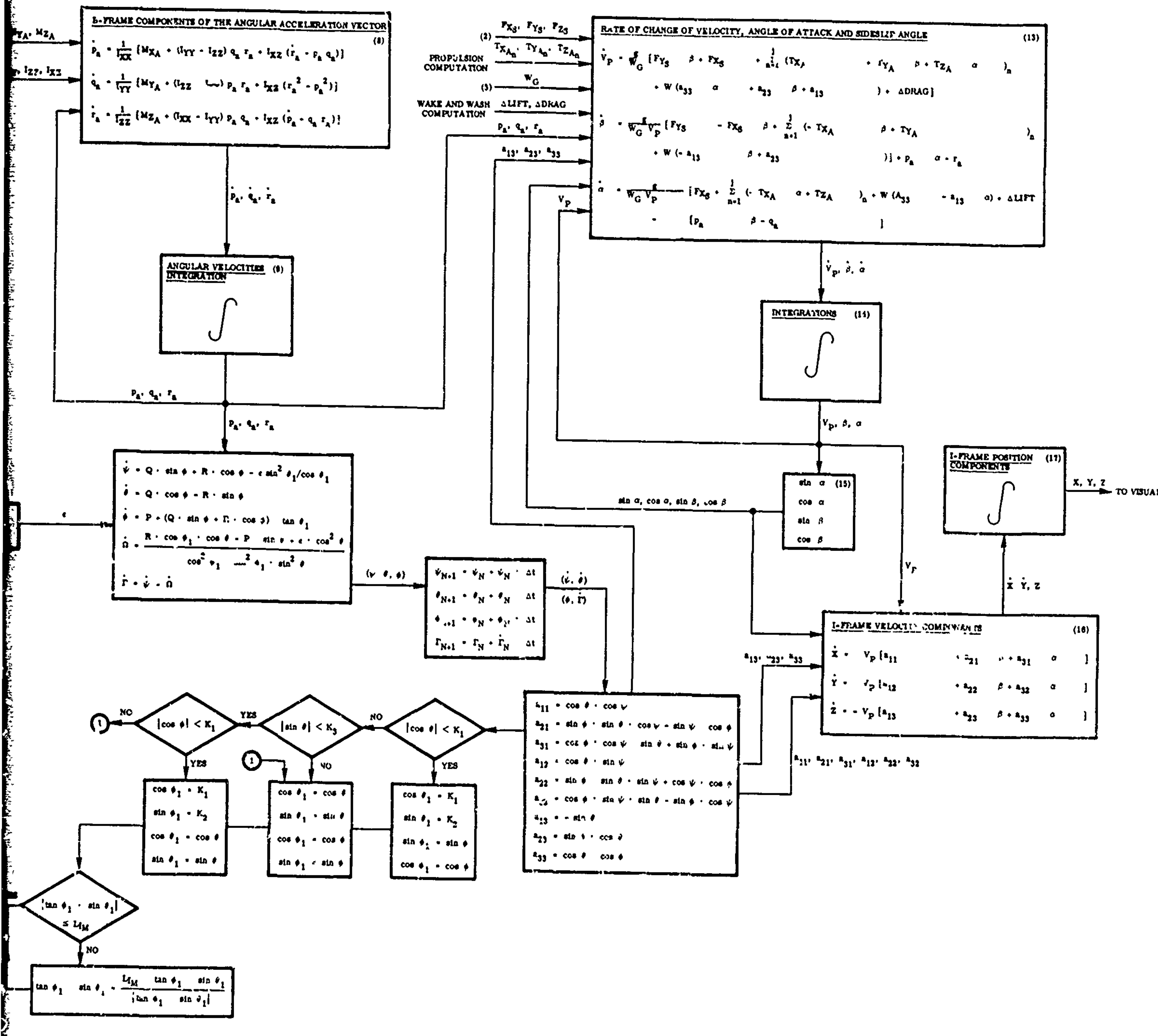
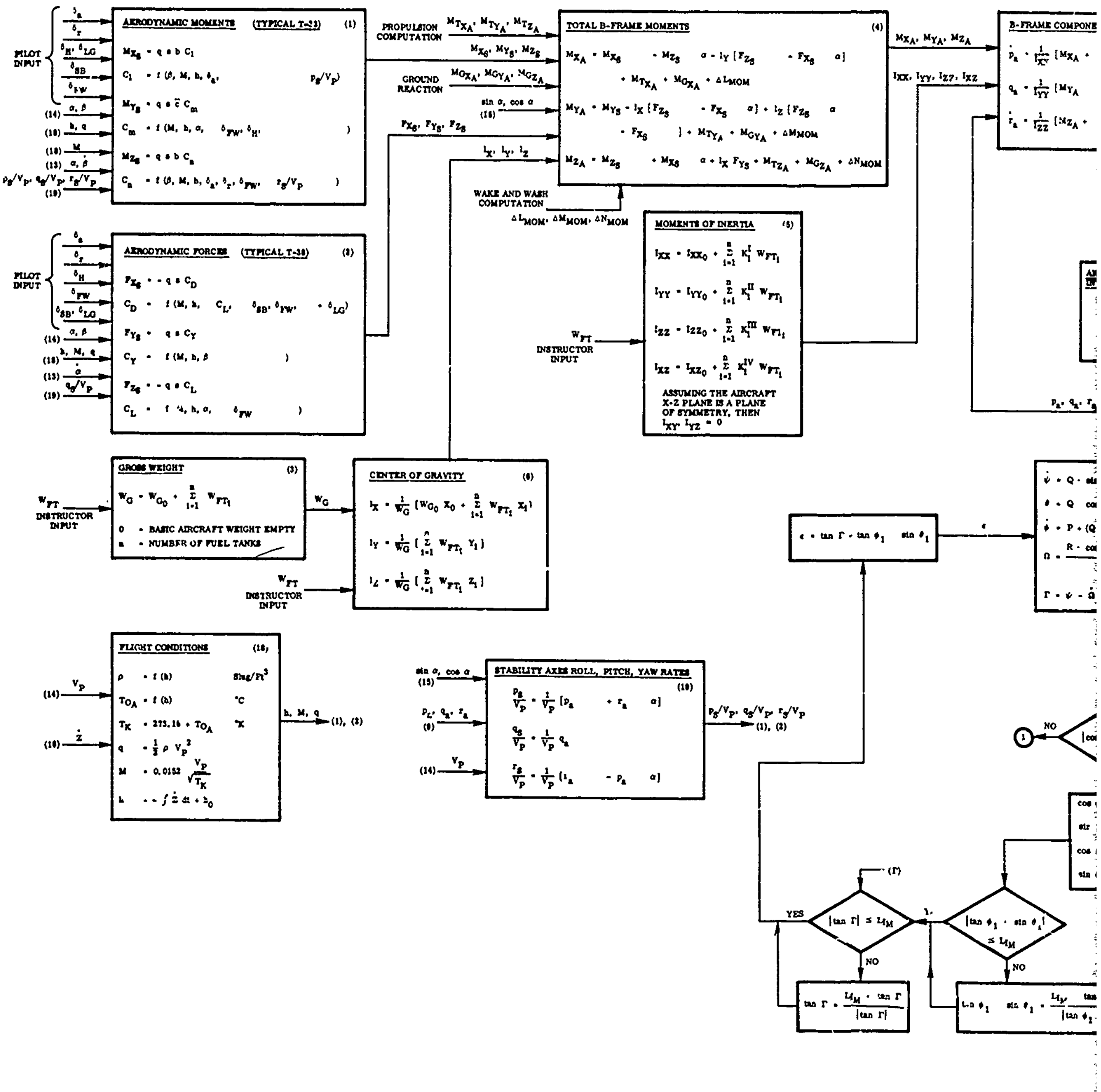


Figure 7 SIMULATOR FLIGHT COMPUTATION SYSTEM SIMPLIFIED TO INTERMEDIATE COMPLEXITY LEVEL

B.



AERODYNAMIC MOMENTS (TYPICAL T-38) (1)
PILOT INPUT
$M_{X_S} = q\,s\,b\,C_l$
$C_l = f(\beta, M, h, \delta_a, \ldots\ p_S/V_P)$
$M_{Y_S} = q\,s\,\bar{c}\,C_m$
$C_m = f(M, h, \alpha, \delta_{FW}, \delta_H)$
$M_{Z_S} = q\,s\,b\,C_n$
$C_n = f(\beta, M, h, \delta_a, \delta_r, \delta_{FW}, r_S/V_P)$
PROPULSION COMPUTATION
GROUND REACTION
TOTAL B-FRAME MOMENTS (4)
WAKE AND WASH COMPUTATION
$\Delta L_{MOM}, \Delta M_{MOM}, \Delta N_{MOM}$
B-FRAME COMPONE
AERODYNAMIC FORCES (TYPICAL T-38) (2)
$F_{X_S} = -q\,s\,C_D$
$C_D = f(M, h, C_L, \delta_{SB}, \delta_{FW}, \delta_{LG})$
$F_{Y_S} = q\,s\,C_Y$
$C_Y = f(M, h, \beta)$
$F_{Z_S} = -q\,s\,C_L$
$C_L = f(M, h, \alpha, \delta_{FW})$
MOMENTS OF INERTIA (5)
$I_{XX} = I_{XX_0} + \sum_{i=1}^{n} K_i^I W_{FT_i}$
$I_{YY} = I_{YY_0} + \sum_{i=1}^{n} K_i^{II} W_{FT_i}$
$I_{ZZ} = I_{ZZ_0} + \sum_{i=1}^{n} K_i^{III} W_{FT_i}$
$I_{XZ} = I_{XZ_0} + \sum_{i=1}^{n} K_i^{IV} W_{FT_i}$
ASSUMING THE AIRCRAFT X-Z PLANE IS A PLANE OF SYMMETRY, THEN $I_{XY}, I_{YZ} = 0$
INSTRUCTOR INPUT
GROSS WEIGHT (3)
$W_G = W_{G_0} + \sum_{i=1}^{n} W_{FT_i}$
0 = BASIC AIRCRAFT WEIGHT EMPTY
n = NUMBER OF FUEL TANKS
CENTER OF GRAVITY (6)
FLIGHT CONDITIONS (18)
$\rho = f(h)$ Slug/Ft^3
$T_{OA} = f(h)$ °C
$T_K = 273.16 + T_{OA}$ °K
$q = \frac{1}{2}\rho V_P^2$
$M = 0.0152\,\frac{V_P}{\sqrt{T_K}}$
STABILITY AXES ROLL, PITCH, YAW RATES (19)
$\frac{p_S}{V_P} = \frac{1}{V_P}(p_a + r_a\,\alpha)$
$\frac{q_S}{V_P} = \frac{1}{V_P} q_a$
$\frac{r_S}{V_P} = \frac{1}{V_P}(r_a - p_a\,\alpha)$
YES
NO

A1

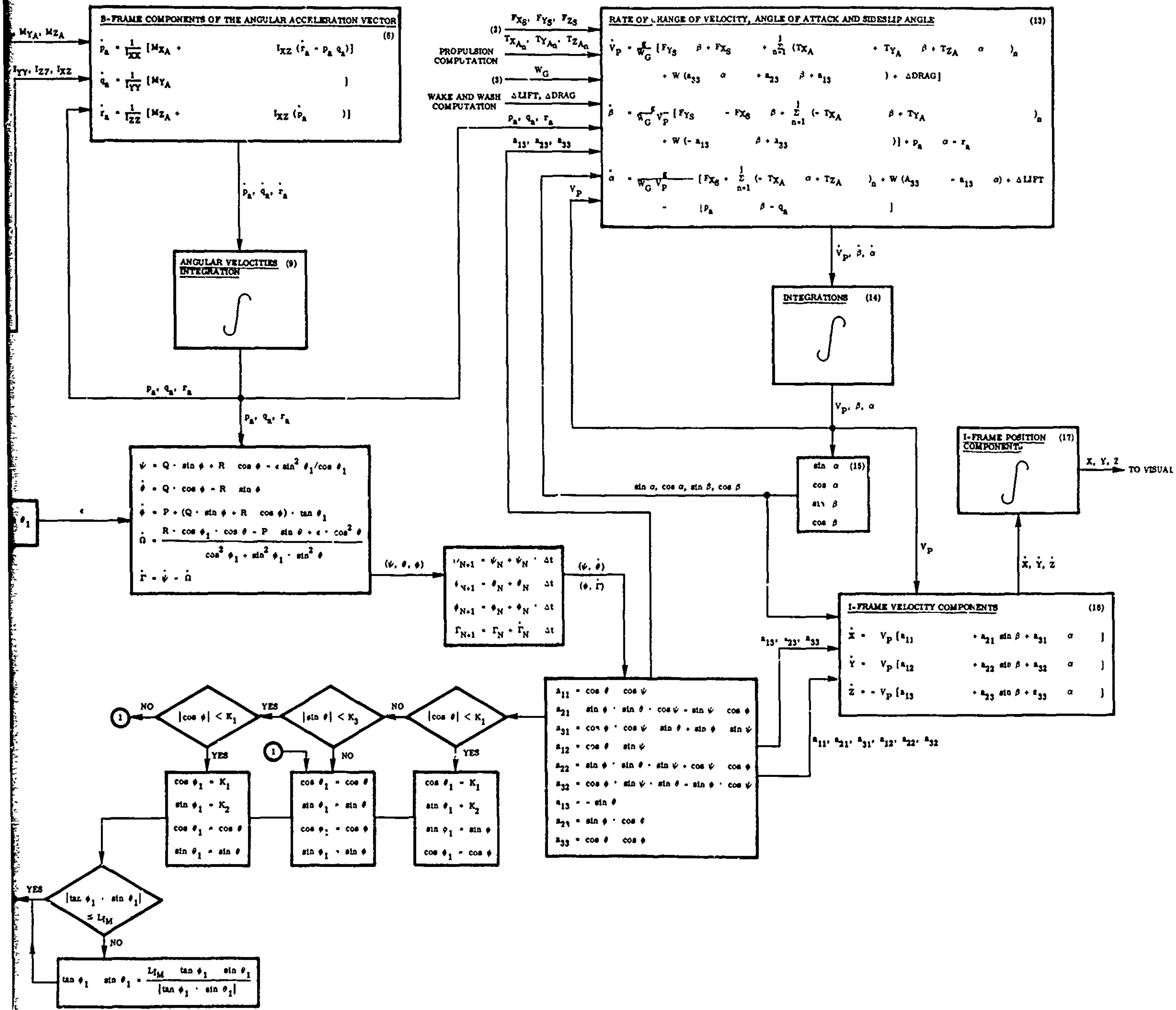


Figure 8 SIMULATOR FLIGHT COMPUTATION SYSTEM SIMPLIFIED TO MINIMUM COMPLEXITY LEVEL

B.

β	Aerodynamic angle of sideslip, defined as the angle between the V_P vector and the projection of the V_P vector onto the plane of symmetry, positive if the V_P vector lies to the right of the aircraft plane of symmetry (deg)
b	Wing span (ft)
$\bar{c}$	Mean aerodynamic chord (ft)
C_D, C_Y, C_L	Aerodynamic drag, side force and lift coefficients
C_l, C_m, C_n	Aerodynamic roll, pitch and yaw moment coefficients
δ_a	Aileron deflection (deg)
δ_{FW}	Flap deflection (dimensionless)
δ_H	Horizontal stabilizer deflection (deg)
δ_{LG}	Landing gear deflection (dimensionless)
δ_r	Rudder deflection (deg)
δ_{SB}	Speedbrake deflection (dimensionless)
F_{X_S}, F_{Y_S}, F_{Z_S}	Force components along the stability axes (lbs)
h	Geometric altitude (ft)
I_{XX}, I_{YY}, I_{ZZ}	Moments of inertia about the aircraft X, Y, Z axes respectively (slug-ft^2)
I_{XZ}	Product of inertia with respect to the X_A-Z_A plane (slug-ft^2)
k	Arbitrary constant
l_X, l_Y, l_Z	Center of gravity coordinates in the body frame (ft)
M	Mach number
M_{X_S}, M_{Y_S}, M_{Z_S}	Aerodynamic moments about the stability X, Y, Z axes (ft-lbs)
M_{X_A}, M_{Y_A}, M_{Z_A}	Aerodynamic moments about the body X, Y, Z axes (ft-lbs)

$M_{T_{X_A}}, M_{T_{Y_A}}, M_{T_{Z_A}}$	Thrust moments about the body X, Y, Z axes (ft-lbs)
$M_{G_{X_A}}, M_{G_{Y_A}}, M_{G_{Z_A}}$	Ground reaction moments about the body X, Y, Z axes (ft-lbs)
p_A, q_A, r_A	Magnitude of the projection of the absolute rotational velocity vector on the X, Y, Z body axes (rad/sec)
p_S, q_S, r_S	Magnitude of the projection of the aircraft absolute velocity vector on the X, Y, Z stability axes (rad/sec)
q	Dynamic pressure (lb/ft^2)
ρ	Air density (slug/ft^3)
s	Wing area (ft^2)
T_K	Absolute ambient temperature (°K)
T_{O_A}	Outside air temperature (°C)
V_P	Aircraft velocity vector relative to the atmosphere (ft/sec)
W_G	Aircraft total gross weight (lbs)

3.3.2 Engine Simulation

The use of digital computation permits a rigorous approach to engine simulation based on full application of the laws of aero-thermodynamics and dynamics to each major component of the engine system. When the various major components are properly integrated, the result is a "dynamic analog" of the engine as it operates in the aircraft. Such a model is completely flexible and capable of simulating any configuration of the engine and its related controls and systems.

A math model of the simulated engine should be designed in modular component form to allow changing or replacement of any section of the simulated engine. This approach allows for degradation of the engine system with minimum amount of program and/or design changes. It should be noted, however, that the design of an engine is not particularly amenable to degradation. Figure 9 is a typical engine simulation flow chart illustrating the modular design approach.

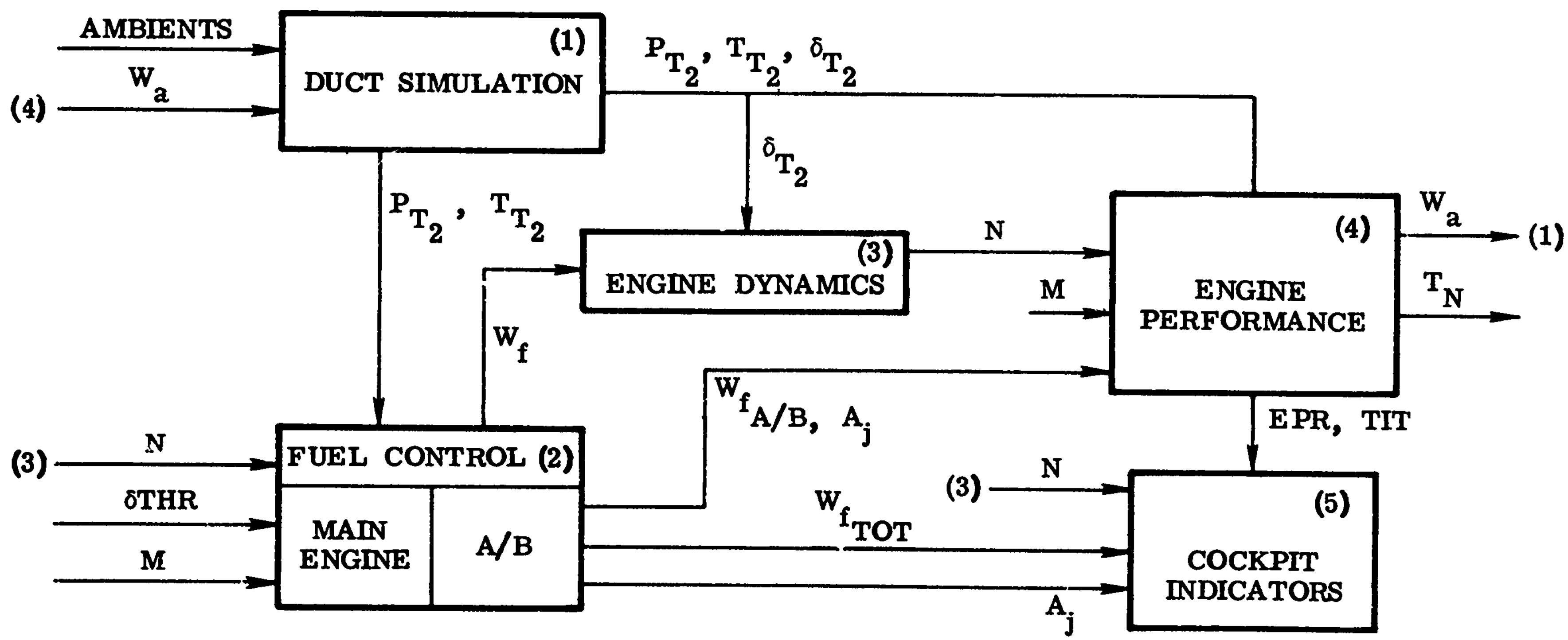


Figure 9 MODULAR ENGINE CONCEPT DIAGRAM

Possible degradation of the engine modules is as follows:

1) Duct Simulation - Simplify to constant flow duct

2) Fuel Control - Linearize fuel control equations

3) Engine Dynamics - Linearize the acceleration-deceleration equations

4) Engine Performance - Simplify the functional dependencies used in the performance computations

The symbols used in Figure 9 are defined as follows:

A_J	Nozzle area
EPR	Engine pressure ratio
N	Rotor speed
P_{T_2}	Total compressor face pressure
TIT	Total inlet temperature
T_{T_Z}	Total compressor face temperature
W_a	Airflow
W_f	Fuel flow - main engine
$W_{f_{A/B}}$	Fuel flow - afterburner only
T_Z	Total compressor inlet pressure ratio
δTHR	Throttle angle
T_N	Total thrust

3.3.3 Jet Wake and Downwash Simulation

One of the training phases which has been singled out as a separate category for training investigation is that of formation flying. Since the intent of the UPTRSS is to provide a high-fidelity simulation facility in which simulation fidelity degradation studies may be conducted, the aerodynamic effects of formation flying should be included. Generally speaking, current-state-of-the-art trainers do not account for such effects

owing to the complexity of their generation and the small amount of formation training done in flight simulators. Although current state-of-the-art simulators do not include jet wake and downwash simulation, an approach to the simulation of these effects was developed by Link for the SMK-27 Aerial Refueling Visual System, a project that was terminated prior to the generation of actual simulation hardware.

The "wake and wash" model proposed herein and mathematically illustrated in Figure 10 is a simplification in itself in that it accounts only for lag or slot aircraft relative velocity changes due to the precession of the lead aircraft and does not account for potential temperature and density changes. It should be noted that "lead" and "lag" as used herein refer respectively to the forward or first aircraft in formation and the wing or slot aircraft following.

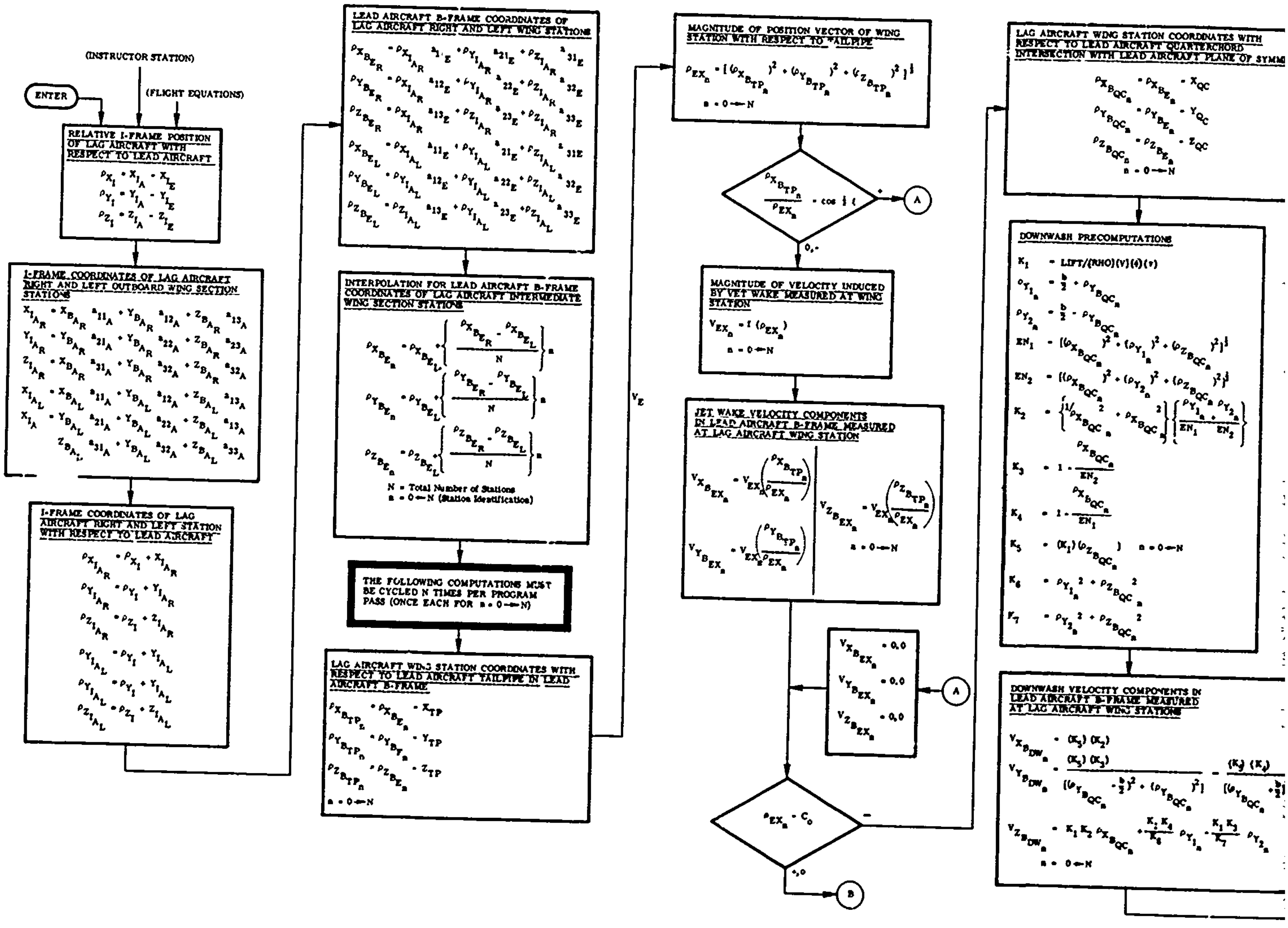
The model shown in Figure 10 is computationally time-consuming even in its simplified state. The jet wake is described by a high-velocity exhaust gas region, cone-shaped with apex originating at the tailpipe of the lead aircraft. The exhaust gas velocity within this region may be described as a function of distance to tailpipe and the exhaust gas velocity vector lies along the line-of-sight vector between the point in question and the tailpipe. The total downwash velocity vector is composed of the summation of three downwash vectors at the point in question. The three downwash vectors are described by implementing the "horseshoe vortex" philosophy and determining the combined circulation strength of each of the two trailing-edge vortices and the airfoil vortex. These velocity vectors are summed at the points in question, which lie at predetermined discrete points on the lag aircraft wing. The effect of the velocity change or "relative wind" change on the lift and drag provided by that particular wing station is computed and summed for as many wing stations as employed. The resultant change in lift and drag and the associated moments are supplied to the flight equations of motion. The primary inputs to the wake and wash model are lead and lag aircraft attitude information and either inertial position of lead and lag aircraft or the relative position of the lag aircraft with respect to the lead aircraft.

The model lends itself to degradation by decreasing the number of lag aircraft wing stations considered and also considering only the Z_B component of downwash velocity. Complete degradation, of course, would be to bypass the model completely.

The symbols used in Figure 10 are defined as follows:

$(XYZ)_{I_A}$	Inertial position coordinates of lag aircraft
$(XYZ)_{I_E}$	Inertial position coordinates of lead aircraft

$\rho(XYZ)_I$	Inertial position coordinates of lag aircraft with respect to lead aircraft
aij_A	B to I frame direction cosines of lag aircraft
aij_E	B to I frame direction cosines of lead aircraft
$(XYZ)_{B_{A_R}}$	Lag aircraft B-frame coordinates of outboard right wing station
$(XYZ)_{B_{A_L}}$	Lag aircraft B-frame coordinates of outboard left wing station
$\rho(XYZ)_{I_{A_R}}$	Inertial frame coordinates of lag aircraft right wing station with respect to lead aircraft
$\rho(XYZ)_{I_{A_L}}$	Inertial frame coordinates of lag aircraft left wing station with respect to lead aircraft
$\rho(XYZ)_{B_{E_R}}$	Lead aircraft B-frame coordinates of lag aircraft right wing station
$\rho(XYZ)_{B_{E_L}}$	Lead aircraft B-frame coordinates of lag aircraft left wing station
$\rho(XYZ)_{B_{E_n}}$	Lead aircraft B-frame coordinates of lag aircraft intermediate wing stations
$(XYZ)_{TP}$	Lead aircraft B-frame coordinates of lead aircraft tailpipe
$\rho(XYZ)_{B_{TP_n}}$	Lead aircraft B-frame coordinates of lag aircraft wing stations with respect to lead aircraft tailpipe
EX_n	Distance between lead aircraft tailpipe and lag aircraft wing station
V_{EX_n}	Magnitude of jet wake velocity at lag aircraft wing station
$\rho(XYZ)_{B_{EX_n}}$	Lead aircraft B-frame components of jet wake velocity measured at lag aircraft wing stations
Σ	Assumed interior apex angle of jet wake cone
$\rho(XYZ)_{B_{QC_n}}$	Lead aircraft B-frame coordinates of lag aircraft wing stations measured with respect to lead aircraft quarter-chord intersection with plane of symmetry


(INSTRUCTOR STATION)
ENTER
(FLIGHT EQUATIONS)
RELATIVE I-FRAME POSITION OF LAG AIRCRAFT WITH RESPECT TO LEAD AIRCRAFT
I-FRAME COORDINATES OF LAG AIRCRAFT RIGHT AND LEFT OUTBOARD WING SECTION STATIONS
I-FRAME COORDINATES OF LAG AIRCRAFT RIGHT AND LEFT STATION WITH RESPECT TO LEAD AIRCRAFT
LEAD AIRCRAFT B-FRAME COORDINATES OF LAG AIRCRAFT RIGHT AND LEFT WING STATIONS
INTERPOLATION FOR LEAD AIRCRAFT B-FRAME COORDINATES OF LAG AIRCRAFT INTERMEDIATE WING SECTION STATIONS
N = Total Number of Stations
THE FOLLOWING COMPUTATIONS MUST BE CYCLED N TIMES PER PROGRAM PASS (ONCE EACH FOR n = 0→N)
LAG AIRCRAFT WING STATION COORDINATES WITH RESPECT TO LEAD AIRCRAFT TAILPIPE IN LEAD AIRCRAFT B-FRAME
MAGNITUDE OF POSITION VECTOR OF WING STATION WITH RESPECT TO TAILPIPE
MAGNITUDE OF VELOCITY INDUCED BY JET WAKE MEASURED AT WING STATION
JET WAKE VELOCITY COMPONENTS IN LEAD AIRCRAFT B-FRAME MEASURED AT LAG AIRCRAFT WING STATION
LAG AIRCRAFT WING STATION COORDINATES WITH RESPECT TO LEAD AIRCRAFT QUARTERCHORD INTERSECTION WITH LEAD AIRCRAFT PLANE OF SYMM
DOWNWASH PRECOMPUTATIONS
DOWNWASH VELOCITY COMPONENTS IN LEAD AIRCRAFT B-FRAME MEASURED AT LAG AIRCRAFT WING STATIONS

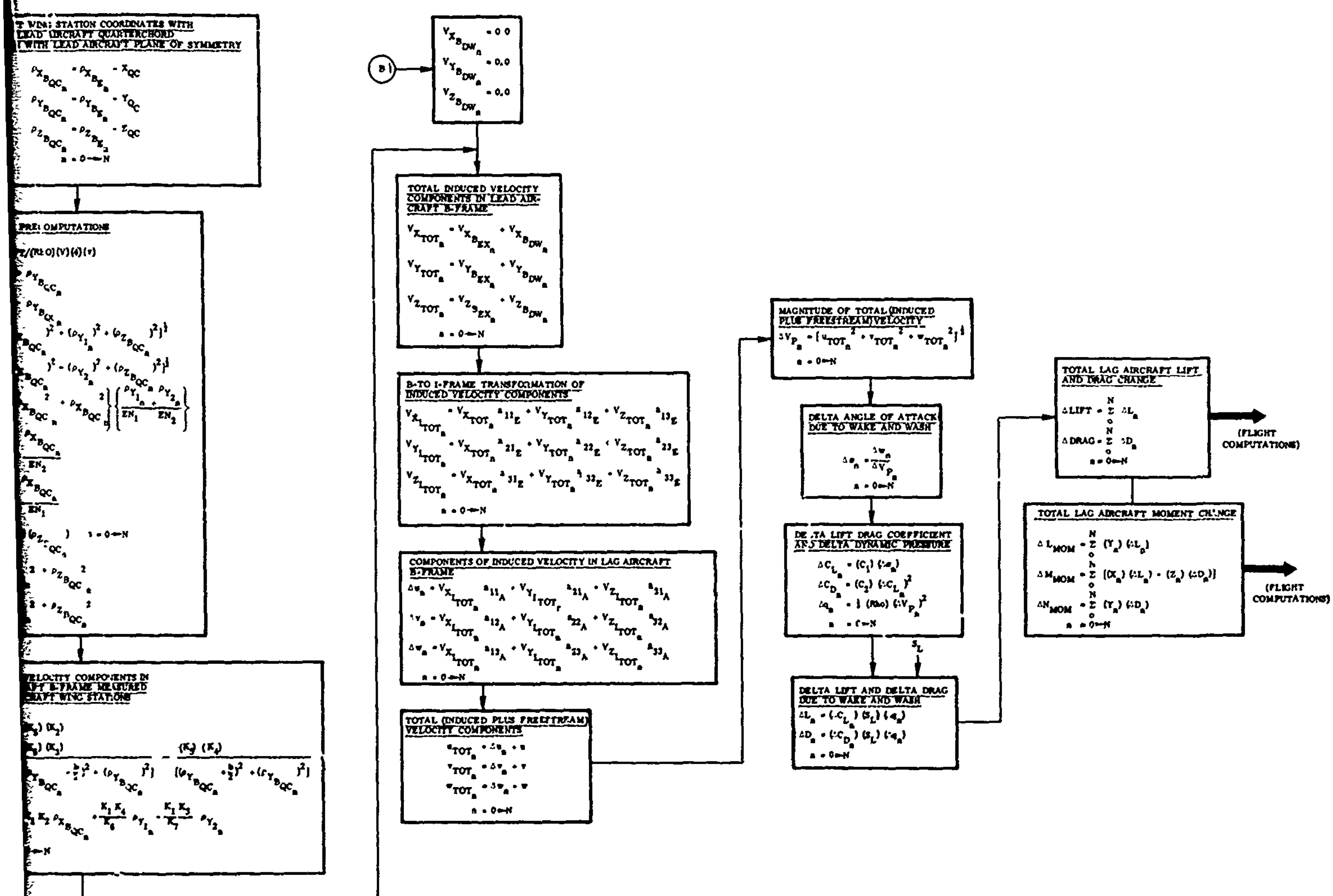


Figure 10 FORMATION WAKE AND DOWNWASH PROBLEM GENERATION

B.

$K_1, K_2, K_3, K_4, K_5, K_6,$ $EN_1, EN_2, Y_{1_n}, Y_{2_n}$	Downwash precomputations
$V(XYZ)_{B_{Dw_n}}$	Lead aircraft B-frame components of downwash velocity measured at lag aircraft wing stations
$V(XYZ)_{TOT_n}$	Summation of jet wake and downwash induced velocity measured at lag aircraft wing stations in lead aircraft B-frame
$V(XYZ)_{I_{TOT_n}}$	Total induced velocity components at lag aircraft wing stations transferred into I-frame
$(u, v, w)_n$	Total induced velocity components at lag aircraft wing station transferred into lag aircraft B-frame
$(u, v, w)_{TOT_n}$	Total "wind" velocity components at lag aircraft wing station in lag aircraft B-frame
V_{P_n}	Magnitude total "wind" velocity at lag aircraft wing stations
$\Delta\alpha_n$	Change in lag aircraft wing station effective angle of attack due to the presence of wake and/or wash
ΔC_{L_n}	Change in lag aircraft wing station lift coefficient due to presence of wake and/or wash
ΔC_{D_n}	Change in lag aircraft wing station drag coefficient due to presence of wake and/or wash
Δq_n	Change in dynamic pressure at lag aircraft wing station due to presence of wake and/or wash
ΔL_n	Change in lag aircraft wing station lift contribution due to presence of wake and/or wash
ΔD_n	Change in lag aircraft wing station drag contribution due to presence of wake and/or wash
ΔLIFT	Change in lag aircraft lift due to wake and/or wash
ΔDRAG	Change in lag aircraft drag due to wake and/or wash
$\Delta(LMN)_{MOM}$	Lag aircraft induced moments due to wake and wash considerations

3.3.4 Degradation

One of the primary areas of potential simulation research is that of investigating ways in which greater training capability may be afforded without additional expenditure devoted to computational facilities. Conversely, the investigation can lead to ways in which the same simulation may be afforded with less expenditure for computational facilities. The key to success in this area lies in the ability to identify areas of current simulator software that may be degraded, with the associated degradation of simulation performance, without incurring a loss of training value. This procedure may also be applied, conversely, in ascertaining what capabilities, in terms of training value, are not "paying their way" with respect to their demands upon the computational facilities. Such an investigation can lead to closer matching of the form and extent of the associated software with the type, accuracy, and extent of aircraft data available. A mismatch in this area results in loss of performance with no savings in computational expenditure.

It is anticipated that the software employed in the UPTRSS simulators will be constructed in a manner which will permit the investigator to execute a mission phase employing the complete software package in high-fidelity simulation. The effects and outputs of this simulation will be noted for reference use. Then, in systematic progression, the investigator may repeatedly degrade the software capability and compare mission reruns with the base or reference execution. The progressively larger loss in training value may then be compared, stage by stage, against the computational savings achieved by the degradation process.

Degradation may be accomplished with respect to either the extent or the fidelity of simulation, or both. The extent of the simulation may be degraded by the exclusion of computational terms individually or in groups, or perhaps by the exclusion of complete subsystem math models. The fidelity of simulation may be degraded by the substitution of constants for variables within certain areas of the math models. The computational fidelity may also be affected by the iteration rate employed in executing the program. The iteration rate may be treated as a variable within the UPTRSS and this subject is covered under the section of this report dealing with math models. Fidelity will also be affected by optional use of small-angle assumptions (extent is somewhat affected also in that some flight terms drop out under small-angle assumptions).

The UPTRSS software should be designed in such a manner as to permit on-line capability, via a suitable input device, to alter the extent and fidelity of the simulation computations. Such alterations would be implemented during the freeze and/or reset operations and would not be a real-time capability in the true sense. The investigator should, as a minimum, be afforded the capability of interrogating the computer for a status output of all alterations made in the high-fidelity software base (see also Section 4).

Degradation capability can be a very useful tool within the UPTRSS software; however, it is best if all software, and particularly that which may be subject to degradation, be formulated from physical models that are readily understood by the investigators. To this end an attempt should be made within the high-fidelity simulation package to eliminate abstract parameters such as quaternions. Wherever possible, methods with "real world" visualizations, such as Euler angles, should be employed.

3.4 GENERAL AIRCRAFT SYSTEMS

3.4.1 Fuel Management, Hydraulic, and Electrical Management Systems

For both T-37 and T-38 simulators, the fuel management, electrical management, and hydraulic systems should be simulated in such a way that the pilot can exercise all aspects of these systems. A high-fidelity simulation model of these systems – i.e., a dynamic model that admits to fluid inertia, viscosity pressure drops across valves, or, in the case of the electrical system, a complete system transfer function — is certainly not required for training. A nondynamic model with fluctuations superimposed on the related indicators. where required, has proven adequate in past simulators and would appear to meet training requirements in this instance.

No systematic degradation capability could apply in these areas because the systems would be programmed at the simplest level to begin with. The only meaningful degradation would be to bypass the system completely and mask the cockpit instruments in question with constant nominal values.

3.4.2 Flight Controls

The stick and pedal forces experienced in a T-37 aircraft are a result of aerodynamic loading, friction, system inertia, and stretch.

Simulation could be accomplished by electromechanical, electropneumatic, or electrohydraulic means. The T-4 trainer utilizes an electropneumatic control loading system. Although the T-4 system has reasonable fidelity, it is not flexible with respect to systematic degradation of simulation fidelity. Currently, most simulators use electrohydraulic control loading when high-fidelity simulation is desired. Electrohydraulic control loading units are extremely flexible and appear ideally suited for high-fidelity simulation with subsequent fidelity degradation necessitated by degradation studies.

The stick and pedal forces experienced in a T-38 aircraft are artificially generated by onboard control loading units. Current T-26

trainers use an electrohydraulic control loading unit. It appears that an electrohydraulic system is ideally suited to the T-38 simulation device.

T-38 aircraft has pitch and yaw stability augmentation. These systems move the elevator and rudder but do not reposition the stick and pedals. Their transfer functions can be readily determined as a math model which can be included as part of the motion equations.

A full-fidelity simulation of the flight controls for an aircraft such as the T-37 would require solving the differential equations which describe the complete control loading system. Such a math model would admit to distributed inertias, distributed friction, distributed stretch, lags in the development of aerodynamic forces because of control surface rotational acceleration and rates. Aerodynamic force changes are related to aircraft accelerations and rates. The transfer function of the hydraulic control loading unit would have to be considered and compensated for. Such a computation would have to be, at least in part, analog or of a high digital computation rate because the delays caused by customarily accepted integration quadratures and input/output sequencing would be intolerable if a normal digital computation rate were utilized. Such a simulation is within the current state of the art; however, the increase in computation equipment does not appear warranted for the UPTRSS. Current simulators achieve a high-fidelity simulation at reasonable cost by treating friction, stretch, and inertias as lumped, rather than distributed, parameters by assuming that aerodynamic forces build up instantaneously, and by neglecting the secondary effects of aircraft motion on the aerodynamic control surface loads. A control loading simulation such as this, with some capability for systematic degradation, appears adequate for the UPTRSS.

3.4.3 Ejection System

For both T-37 and T-38 simulators it appears most desirable to incorporate an ejection seat with all the triggering logic activated. When the proper ejection sequence is followed, rather than have the canopy fly open (which would damage associated visual equipment) it would be sufficient to have the canopy automatically unlatch and rise on its pressure seal. The actual ejection charge could be simulated by an electrical solenoid seat thumper. The operator should be able to fail the automatic release in order to require the student to manually release the canopy before he can complete ejection or finish his ejection by simulated firing through the canopy, in which case the seat thumper should be activated with the canopy still latched. This ejection simulation would be necessary only in the UPTRSS cockpit associated with the flight phases in which ejection training is most desirable.

Degradation of ejection simulation can be accomplished by simply restructuring the logic computation in the computer to the desired level of simulation.

3.4.4 Cockpit Environmental Control System

All cockpits should have a cabin air-conditioning system that to all outward appearances operates as in the real aircraft. It is unnecessary to supply heated air, but for pilot comfort and realism it appears desirable to have cooled air available and controllable by the aircraft controls. Whether a central air conditioning system is utilized or separate air conditioners are provided for each cockpit depends upon the overall facility configuration, and the decision may be left to the contractor who builds the facility.

The T-38 aircraft has a pressurized cabin and a cabin altimeter. The pressurization system should be simulated to the extent that the cabin altimeter reads correctly and is properly affected by manipulation of the cabin pressurization controls.

No special degradation capabilities need to be incorporated in the cabin air conditioning simulation. The absence of need for cooled air could be determined by turning off the cooling capability of the blower. Air conditioning and pressurization controls could be simply rendered inoperative mechanically or electrically. The cabin altimeter could be masked if desirable.

3.4.5 Miscellaneous Systems

3.4.5.1 Oxygen System

This system should be simulated so that the management and usage is the same as in the actual aircraft. As in current simulators, air should be used in lieu of oxygen for safety purposes. Considering possible simulation degradation, it appears that a constant indication of remaining oxygen set at some nominal value would be reasonable. For those cockpits which are utilized for low-level flight only, the simulated oxygen system need not be operable.

3.4.5.2 Anti-G System

This system should be simulated. Management and usage should be the same as in the actual aircraft. The system is so simple that no possibility of progressive degradation exists. The T-37 aircraft does not have an anti-G system; hence only the T-38 cockpits associated with airwork and aerobatics phases of training require anti-G simulation.

3.4.5.3 Pitot-Static and Stall Warning Systems

Management of this system consists of application of pitot heat under simulated icing conditions. Degradation of simulation does not

appear desirable — i.e., either the effects of ice and application of pitot heat are simulated or not. Simulation of the pitot static system is applicable to both T-37 and T-38 aircraft. Stall warning transducer vane heat is applicable to T-37 aircraft only — the single pitot heat switch applies heat to both pitot tube and stall warning transducer vane. It is necessary to simulate pitot system icing and pitot heat for those cockpits associated with the phases of training in which aircraft management under icing conditions is desirable.

3.4.5.4 Caution, Warning and Indicator Light System

The T-38 aircraft has a caution warning panel and it should be simulated such that it is activated for all instructor-inserted malfunctions which would activate the lights in the actual aircraft. T-37 aircraft does not have a caution warning panel as such, but it does have various caution warning indications. The same simulation philosophy applies to the T-37 simulator as applies to the T-38 simulator.

Simulation degradation does not appear desirable; however, only the indications associated with the desirable instructor-inserted malfunctions need be simulated in the cockpits related to specific training phases.

3.5 COMMUNICATION AND NAVIGATION AIDS

The T-4 and T-26 trainers built by Link include a state-of-the-art, high-fidelity simulation of all the communication and navigation equipment currently carried in the T-37 and T-38 aircraft. It is felt that the same type of simulation is required for the UPTRSS. Any phase of training could feasibly utilize all the equipment; therefore it seems reasonable that all cockpits should have a full complement of equipment simulated.

It is quite possible that at a later date new or different communication and/or navigation aids may be required. If they are in the actual aircraft, then of course their respective control panels can be fitted into the simulated cockpits. To this end it becomes desirable that instrument panel mountings be designed initially for ease of interchangability, elimination, and addition. For replacements the computation requirements will probably be in the same order of magnitude or slightly increased. However, if the new equipment is additive, then the computation requirements will increase accordingly; this of course implies that spare computational capability should be available.

Simulation of communication and navigation equipment does not readily lend itself to degradation. A limited amount of simplification is possible, such as elimination of squelch circuit simulation and simplified models for marker beacon cones. It is possible to conduct some of the training phases without simulating all of the equipment. If all the equipment

is simulated in each cockpit, it is a simple matter to deactivate the desired equipment by simply eliminating the program which simulates the specific piece of equipment. Following is a breakdown showing the training phases associated with each cockpit and the minimum navigation and communication equipment simulation requirements. The UPTRSS should have the capability of simulating to any degree between full simulation and this minimum.

T-37	T-38
1. Interphone	1. Interphone
2. UHF	2. UHF
3. VHF (VOR)	3. TACAN
4. IFF-SIF	4. ILS (M/B, LOC, G/S)
	5. IFF-SIF

	Takeoff and Go Around	Airwork and Aerobatics	Extent of Simulation
T-37	1, 2, 3, 4	1, 2, 3, 4	High-fidelity
	Not Applicable	1, 2, 3, 4	Minimum if flight from field to operating area and return is required
	1, 2 (Bare Minimum Only)	1	Bare minimum if training phase does not necessarily include flight from field and return
	Formation	**Low Level**	**Extent of Simulation**
T-38	1, 2, 3, 4, 5	1, 2, 3, 4, 5	High-fidelity
	1, 2	1, 2, 3, 4, 5	Minimum if flight from field to operating area and return is required
	1, 2	1, 2, 3, 4, 5	Bare minimum if training phases does not necessarily include flight from field and return

These tabulations are based on the following assumptions:

1) Assume navigation gear is needed in flight from field to operating area.

2) The type of navigation gear necessary for terminal approach depends on landing field facilities.

3) For low-level flight most navigation gear is unusable due to line-of-sight limit (T-37 - 2, 3, 4; T-38 - 2, 3, 5)

4) Night flying may include both night airwork (heavy dependence on instruments) and night navigation.

4. INSTRUCTOR/OPERATOR/EXPERIMENTER STATIONS

4.1 MODES OF OPERATION

The control and display facilities required for UPTRSS instructor-operators and researchers depend on many factors. This section discusses some of these requirements and indicates the ways in which state-of-the-art equipment requirements may be implemented to satisfy the needs of the facility.

The facility concept is influenced to a large extent by the modes of operation under which research and training can be carried out. The availability of four cockpits could allow:

1) Operation of each cockpit for individual research projects

2) Operation of all cockpits separately but studying a coordinated problem

3) Operation of the two T-37 cockpits on the same problem and the two T-38 cockpits on a separate problem

4) Operation of all four cockpits on the same coordinated research problem

Additional motion and visual simulation capability will allow a large variety of separate and interconnected modes of research to be carried out.

It is desirable to design the computer, instructor-operator, and research facilities in a way that will permit the facility simulation capability to be used in part – i.e., when parts of the equipment are inoperative. This would seem to suggest that the facility should include at least two simulation computers, one computer running two T-37's and the other two T-38's, each with interface facilities to two cockpits and to two instructor-operator consoles (see Section 5). In addition to providing the necessary input and output to both the cockpits and the instructor-operator and research stations, together with other peripheral equipment such as flight path recorders, X-Y plotters, line printers, TTY's, CRT's, etc., which may be required, the simulation computers would also accept input from, and provide research analysis output to, a research computer, the programs of which would be under control of the staff at a research console. The research computer would be provided with considerably more ancillary input/output and peripheral equipment than the two simulation computers. For example, it would not be unreasonable to provide several disc units, several magnetic tape units, card reader, card punch, teletypewriters, line printer, digital plotter, and CRT displays at the research console, if these are deemed to be necessary.

In a facility configured in this way, failure of either simulation computer would allow uninterrupted research on the two unaffected cockpits, while failure of the research computer, which is provided for on-line and off-line analysis of the research results, would simply cause the research facility to revert to an off-line mode of analysis.

4.2 RESEARCH AREA LAYOUT

A proposed layout for the research area is shown in Figure 56 Centrally located is the research console from which all research being carried out at all four cockpits is controlled. In close proximity to the research console are the various hard-copy output devices (line printer, digital plotter) which are likely to provide additional information to the staff at the research console. The number of such output devices cannot be firmly established at this stage; however, it is desirable that all devices of this type be located within easy range of the research console. To permit the research console to be moved, the cabling to the research console should be designed to facilitate freedom of movement. Cabling for the hard-copy output devices should be installed to permit limited freedom of movement such that the devices may be best positioned to suit the prevailing research.

If it is desired to evaluate the effectiveness of a plotter in comparison with an analog XY recorder at the instructor console, both equipments should be wired such that they can be moved to a position adjacent to any instructor console. While the immediate application of a line printer or teletypewriter to the instructor task is not clear, it may be considered necessary to configure the system such that these devices may also be moved to any position in the mezzanine research area. It should be noted that there may be cable length limitations for all computer output devices.

Located adjacent to the access platform to the simulator cockpits will be individual instructor consoles. The present recommendation is to provide maximum and identical facilities for the control of each simulated cockpit. The research area will, therefore, contain four instructor consoles containing conventional instrumentation (resembling the T-4 and T-26 instrument trainers) and four advanced instructor stations containing one or more CRT displays (see Figure 56). Analog X-Y recorders, similar to the T-26 analog recorder, will also be present. In order to provide the necessary flexibility and versatility at the facility, all consoles should be wired in a manner which permits any two adjacent consoles to be placed close to one another. It should be possible for the recorder to be placed in any position near either console.

To eliminate the presence of above-the-floor cable runs, it is suggested that the console cabling be run in a circulating duct near the outside of the research area. Since it is most likely that the consoles will

always be located adjacent to a cockpit and close to the periphery of the research (mezzanine) area, the consoles will always be close to the cable duct, to allow access.

4.2.1 Research Console

4.2.1.1 Preprogrammed Research

In order to centralize the process of research, it is essential that the research console be provided with a means of initiating and operating one of a series of preprogrammed research exercises. The facilities provided should also include a means for observing the progress of the preprogrammed exercise (for example, by status lights indicating the progress which has been reached, or, if a CRT is present, by a suitable alphanumeric readout). The research console should also be provided with means whereby the research staff may take exception to a preprogrammed exercise sequence if conditions justify this action. The number of different preprogrammed exercises which may be operated simultaneously is, of course, dependent upon the modes of operation intended for the UPTRSS, which were mentioned earlier. In order to ensure that the greatest benefit is derived from the research facility, well-thought-out research programs are essential. The orientation of the research console towards operation in a preprogrammed environment will assist by ensuring that impromptu or unscheduled research is minimized as far as possible.

4.2.1.2 Research Parameter Controls

The research console must also be provided with controls which permit the preprogrammed exercise to be modified in a way not normally permitted in a conventional simulator. This variation may be sufficiently subtle as to be undetectable to either the student or the instructor. Typically, controls should be provided for variation of:

1) Fidelity of simulation (the scope of this variation is the subject of Section 3 of this report)

2) Motion parameters and associated software

3) Visual parameters and associated software

4) Aural parameters

5) Speed of the exercise (slower or faster than real time)

The research parameter controls on the research console should ideally be remotely located from all other types of control since inadvertent operation might be unnoticed and might result in large amounts of abortive research.

The research parameter controls will interact directly with programs within the research computer, which may directly modify the programs in the simulation computers.

The research station should be instrumented to permit changes in the fidelity of simulation due, for example, to alternate motion system drive signal formulations or degradation in aural cue fidelity. These changes could be monitored using CRT display techniques. Not all parameters can be directly monitored on a CRT (e.g., change in focus of a projector), but certainly such information can be entered off-line into the research computer for logging and display as required.

The following section considers the utilization of CRT equipment at the research console.

4.2.1.3 CRT Displays

Since the CRT display has proved to be highly suitable as an input/output and control medium for interaction with a digital computer and its programs, it is appropriate to discuss possible applications of CRT-based control systems at the research console.

4.2.1.3.1 General Applications

Computer-driven CRT display systems are now available as off-the-shelf items suitable for interfacing with almost all types of general-purpose computers. In addition, there are several specialist manufacturers who provide CRT display equipment and also the service of interfacing with the customer's chosen computer.

The technology of design and programming of computer-driven CRT display systems has been well documented. The reader is referred to Display Systems Engineering by H. R. Luxenberg (McGraw Hill Book Company) or Fundamentals of Display Systems by Harry H. Poole (Spartan, MacMillan and Co. Ltd.). This report presents a tabulation (see Figure 11) of the various equipments offered, which is reproduced in detail from Modern Data Systems (the September 1968 issue).

During the course of the study, an attempt has been made to avoid consideration of specific hardware or software. The study has been more concerned with examining the tasks to be performed at the research console, with a view to predicting the display and control requirements which could be met by one or more CRT displays. The applicability of the CRT equipment to monitoring modifications of fidelity of the simulation is discussed in the following paragraphs. (See Figure 11.)

ALPHANU

COMPANY	A. B. DICK	BUNKER-RAMO			BUR-ROUGHS	CCI	CONRAC	CONTROL DATA		DATA DISC	GENERAL ELECTRIC	HONEYWELL			IBM CORP.	
MODEL NO.	Videograph 990	211	Teleregister 212	203	BIDS	CC-301	201	210	212	TDS-1	DATANET-760	303	311	312	2260	2265
SCREEN SIZE (inches)	Any TV receiver	4-3/4 x 3-3/4	4-3/4 x 3-3/4	7-3/4 x 5-1/2	9 x 12	Any TV receiver	8-1/2 x 7-1/2	14 CRT	14 CRT	Any TV receiver	14 CRT	7-3/4 x 5-1/2	4-3/4 x 3-3/4	4-3/4 x 3-3/4	4 x 9	67 sq. in.
CHAR. SIZE (inches)	—	1/4 max.	1/4 max.	1/4 max.	0.15 x 0.115	0.187 x 0.156	1/4 max.	1/4	1/4	0.15 typical	0.16 x 0.12	1/4 max.	1/4 max.	1/4 max.	0.14 x 0.09	0.18 x 0.13 typical
NO. OF CHAR. POSITIONS	512 typical	768 max	768 max.	768 max.	2000	800	888	1000	1000	4000	1196	768 max.	384 max.	384 max.	960 max.	960 max.
CHAR./LINE	32 typical	64 max.	64 max.	64 max.	80	40	37	50	50	85	46	64 max.	32 max.	32 max.	40	40 or 80
NO. OF LINES	16 typical	12 max.	12 max.	12 max.	25	20	24	20	20	48	26 max.	12 max.	12 max.	12 max.	6	15 or 12
CHAR. GENERATOR	matrix		matrix		12 strokes	7 x 5 matrix	7 x 5 matrix	matrix	matrix	7 x 5 or 7 x 10 matrix	12 x 16 Matrix	7 x 5	7 x 5	7 x 5 matrix	7 x 5 matrix	40 strokes
REFRESH RATE/Sec.	60	40	40	40	60	60	60	50	50	30	30	40	40	40	30	54
TYPE OF REFRESH MEMORY	Core	Delay line	Delay line	Delay line	Core	Core	Delay line	Delay line	Delay line	Disc	Delay line	Delay line	Delay line	Delay line	Delay line	Delay line
KEYBOARD	Optional	Numeric	Standard	Standard	Standard	Optional	Standard	Standard	Standard	No	Standard	Standard	Numeric	Standard	Standard	Standard
LIGHT PEN	No	No	No	No	No	Optional	No	No	No	No	No	No	No	No	No	No
FUNCTION KEYS	No	Standard	Standard	Standard	Standard	No	Standard	Standard	Standard	No	Optional	Standard	Standard	Standard	No	Standard
CURSOR OR MARKER	Standard	Standard	Standard	Standard	Standard	Optional	Standard	Standard	Standard	Yes	Yes	Standard	Standard	Standard	Standard	Yes
SPLIT SCREEN	Possible	No	No	No	No	No	No	No	No	Yes	Yes	No	No	No	No	No
TABULATION	No	No	No	No	Standard	Possible	Optional	—	—	No	Yes	No	No	No	No	No
HARD COPY	No	Optional	Optional	Optional	Optional	Optional	No	Optional	No	No	Optional	Optional	Optional	Optional	No	No
GRAPHIC CAPABILITY	No	No	No	No	No	108 x 85 matrix	No	No	No	No	No	No	No	No	No	No
DISPLAYS PER CONTROLLER	No Limit	24 max.	24 max.	24 max.	4 max.	Several	1	12 max.	1	64	32-256	12 max.	12 max.	12 max.	24 max.	24 max.
MAX. I/O RATE (CHAR./SEC.)	—	240	240	240	480	500,000	120	50,000	50,000	300,000	240	240	240	240	240	240

GRAPHIC CRT DISPL

COMPANY	ADAGE, INC.			COMPUTER DISPLAYS	CONTROL DATA CORP.			DIGITAL EQUIPMENT CORP.				INFORMATION DISPLAYS, INC.
MODEL NO.	AGT/10	AGT/30	AGT/50	ARDS	250	270	274	338/339	VDB/I	34	340	IDIIOM
SCREEN (IN.)	12 x 12	12 x 12	12 x 12	6-1/2 x 8-1/4	12 x 12	14 x 14 or 11 x 17		9-3/8 x 9-3/8	Tektronix Scope		9-3/8 x 9-3/8	13 x 13 or 12 x 16
TOTAL LINES	4500	4500	4500	1081	1024	—	—	1024	1024	1024	1024	1600
Refresh Rate/Sec.	40	40	40	Storage tube	40	—	—	30 or 60	Storage tube	—	—	30
LIGHT PEN	Standard	Standard	Standard	No	Standard	Standard	Standard	Standard	No	Optional	Optional	Standard
KEYBOARD	Optional	Optional	Optional	Standard	Standard	No	No	Standard	PDP-8/I	No	No	Standard
TABLET	Optional	Optional	Optional	No	No	No	No	Optional	No	No	No	Optional
JOYSTICK	Optional	Optional	Optional	Optional	No	No	No	Optional	Standard	No	No	Optional
TRACKBALL	Optional	Optional	Optional	No	No	No	No	No	No	No	No	Optional
FUNCTION SWITCHES	Standard	Standard	Standard	Yes	Standard	Standard	Standard	Standard	No	No	No	Standard
VECTOR GENERATION		Point-to-Point 5.5-38 usec.		Point-to-point 1081 x 1415 points 3500 vectors 1/2" per msec.	Point-to-Point 1024 x 1024 7 usec. average	8,000 x 8,000 points		1024 x 1024 points 20-46 usec. per point	Point-to-point 3000 points/sec. 225-1750 vector/sec. Circle generator	1024 x 1024 points		3" in 20 usec. Circle generator Continuous line
CHARACTER GENERATION		Optional Hardware Strokes 15 usec./char.		Standard 4000 char. 2.4 msec./char.	Standard 3.75 usec. per char.	Standard	Standard	Optional Hardware Software 20 usec./char.	Subroutine 350 char./sec.	None	Optional Subroutine Hardware 20 usec./char.	Standard 10 usec./char. 2600 char.
3D	No	Optional	Optional	No	Yes	Yes	Yes	No	No	No	No	—
IMAGE MANIPULATION	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	No	—	Yes
HARD COPY		Optional (Photographic)		No	No	Yes	Yes	No	No	No	No	No
COMPUTER		Includes Ambilog 200 Hybrid Computer		None	Any	For CDC 3300	Includes CDC 1700	PDP-8 PDP-9	PDP-8/I	Any	Any	Any
MEMORY SIZE	4K x 30	8K x 30	16K x 30 plus disc	1081 x 1415	4096 x 24	60K Words	Uses CDC 1700 Memory	In Computer	1024 x 1024	None	In Computer	4096 x 16
MEMORY TYPE	Core	Core	Core	Storage tube	Core	Drum	Core	Core	Storage tube	None	In Computer	Core
MIN. PRICE	60K	Depends	Depends	12.75K	—	—	—	36K + computer	6.5K	3.9K	35K	70K

A,

ALPHANUMERIC CRT DISPLAYS

AL IC	HONEYWELL			IBM CORP.		PHILCO		RADIA- TION	RCA		RAY- THEON	SANDERS ASSOC.		SCIENTIFIC DATA SYSTEMS		STROMBERG-CARLSON		TRANSIS- TOR ELEC.	UNIVAC	
ET-	303	311	312	2260	2265	D-21/20	D-22	6603	70/751	70/752	DIDS-400	720	920	7550	7555	SC-1090	SC-1110 DESC	S-512	Uniscope 3005	300M
	7-3/4 x 5-1/2	4-3/4 x 3-3/4	4-3/4 x 3-3/4	4 x 9	67 sq. in.	7.4 x 10.4	11.2 x 8.4	19 CRT	12 CRT	6-1/2 x 8	6-1/2 x 8-1/2	7-1/2 x 9-1/2	11-1/2 x 15	7 x 10	7 x 10	19 CRT	9 x 7	7-1/2 x 9-1/2	10 x 5	10 x 5
.12	1/4 max.	1/4 max.	1/4 max.	0.14 x 0.09	0.18 x 0.13 typical	0.20 x 0.21	0.689 x 0.359 max.	0.125 x 0.25	—	0.14 x 0.10	0.17 x 0.14 typical	0.13 x 0.08	0.2 x 0 13 typical	0.15 x 0.11		—	—	0 23 x 0.15	0.15 x 0.11	
	768 max.	384 max.	384 max.	960 max.	960 max.	768 max.	1024 max.	4000	1080 max.	1080 max.	1040 max.	1024 max.	2000 max.	2752 max.	2752 max.	—	1000 max.	512 max.	1024	1024
	64 max.	32 max.	32 max.	40	4 or 80	64 or 32	64 or 32	Continu-ous	27-81	54	80 max.	64 max.	81 max.	86 max.	86 max.	—	72 max.	32	64	64
	12 max.	12 max.	12 max.	6	15 or 12	24	12 or 16	Continu-ous	20 max.	20 max.	16 max.	40 max.	—	32 max.	32 max.	—	35 max.	16	16	16
	7 x 5	7 x 5	7 x 5 matrix	7 x 5 matrix	40 strokes	7 x 5 matrix	5 x 12 matrix	Stroke	—	—	Closed curve	16 strokes	22 strokes	Continuous Curve		Charactron tube		16 strokes	Continuous line	
	40	40	40	30	54	60	—	60	60	60	67	46.5	52.5	50	50	—	50	60	60	60
	Delay line	Delay line	Delay line	Delay line	Delay line	Delay line	Core	—	Delay line	Delay line	Delay line	Delay line	Delay line	Delay line	Delay line	Core	Delay line	Core	Core	Core
	Standard	Numeric	Standard	Standard	Standard	Standard	Standard	No	Standard	Standard	Optional	Standard	Standard	Standard	Standard	Optional	Standard	Optional	Standard	No
	No	No	No	No	No	—	—	No	No	No	No	Optional	No	No	No	Optional	No	No	No	Standard
	Standard	Standard	Standard	No	Standard	Standard	Standard	Yes	Yes	No	Optional	Yes	Standard	Yes	Yes	Optional	Standard	Optional	Yes	Yes
	Standard	Standard	Standard	Standard	Yes	Standard	Standard	Standard	Standard	Standard	Standard	Yes	Standard	Standard	Standard	—	Standard	Standard	Yes	Yes
	No	No	No	No	No	—	—	No	Standard	Standard	No	Yes	—	No	No	—	No	Yes	Standard	Standard
	No	No	No	No	No	Standard	Standard	No	Stored format	Stored format	Yes	Yes	—	No	No	—	No	Optional	Yes	Yes
	Optional	Optional	Optional	No	No	Optional	Optional	No	No	No	Optional	No	No	Optional	Optional	No	Optional	No	No	No
	No	No	No	No	No	Optional	Optional	Line segments	No	No	No	No	Vectors	No	No	Yes	No	No	No	No
	12 max.	12 max.	12 max.	24 max.	24 max.	—	24	—	8	1	64	4	—	1	1	1	12	1	1	48 max.
	240	240	240	240	240	120	—	40,000	4800	120	260	47,500	100,000	15	180	—	—	120	240	240

GRAPHIC CRT DISPLAY EQUIPMENT

	UIPMENT CORP.		INFORMA-TION DIS-PLAYS, INC.	INFORMA-TION INTER-NATIONAL	IBM CORP.	SANDERS ASSOCIATES		SCIENTIFIC DATA SYSTEMS	SYSTEMS ENGR. LABS.	TASKER INDUSTRIES			
	34	340	IDIIOM	1060	2250	960/10	960/40	7580	816A	9100	9110	9200	9210
	nix Scope	9-3/8 x 9-3/8	13 x 13 or 12 x 16	10 x 10	12 x 12	14 x 14	14 x 14	10 x 10	10.24 x 10.24	12 x 17.5	12 x 17.5	14 x 14	14 x 14
	1024	1024	1600	1024	1024	1024	1024	1024	1024	1400 x 2048	1400 x 2048	2048	2048
	—	—	30	30	30	60	Variable	30	—	50	50	50	50
	Optional	Optional	Standard	Optional	Optional	Optional	Standard	Standard	Optional	Yes	Standard	Standard	Standard
	No	No	Standard	Optional	Optional	Optional	Standard	Standard	No	Standard	Standard	Standard	Standard
	No	No	Optional	Optional	No	Optional	No	No	No	No	No	No	No
	No	No	Optional	No	No	Optional	No	No	No	No	No	No	No
	No	No	Optional	No	No	Optional	No	No	No	No	No	No	No
	No	No	Standard	Optional	Optional	Optional	Standard	Standard	Optional	Standard	Standard	Standard	Standard
ec. or	1024 x 1024 points		3" in 20 usec. Circle generator Continuous line	200K inches/sec.	Point plotting or line segments 16.8 usec./point	Point-to-point 500K inches/sec. 1024 x 1024 points		1024 x 1024 Dots at 7.2 or 13.2 usec. per point	Vectors up to 1.27" take 14 usec. Over 1.27" take 28 usec.	Points at 4-48 usec. Vectors at 17-54 usec.		Points at 10 usec. Vectors at 12-35 usec	
ec.	None	Optional Subroutine Hardware 20 usec./char.	Standard 10 usec./char. 2600 char.	Standard Mask in tube 5 usec./optional 20 usec./char.	Optional 3848 char. posi-tions — 52 lines at 74 char.	Standard 22 strokes 135 nsec. per stroke		Standard strokes	Op[illegible]nal [illegible] 5 matrix	Standard Strokes 7 usec. per char.	Standard Strokes	Standard Strokes 6.5 usec. per char.	Standard Strokes
	No	No	—	No	No	No	No	No	No	No	No	No	No
	No	—	Yes	No	No	No	No	No	No	No	No	No	No
	No	No	No	No	No	No	No	No	No	No	No	No	No
	Any	Any	Any	Any	Any	Any	Any 24-bit	Sigma 5 or 7	SEL 800	Any	Any	Any	Any
	None	In Computer	4096 x 16	4096 x 8	8192 x 8	In Computer	In Computer	In Computer	In Computer	In Computer	4096 x 24	In Computer	4096 x 24
	None	In Computer	Core	Delay line	—	In Computer	In Computer	In Computer	In Computer	In Computer	Core	In Computer	Core
	3.9K	3[illegible]K	70K	54.25K	76 8K	—	—	58K	20K	—	—	—	—

Figure 11 CRT DISPLAY EQUIPMENT

B.

4.2.1.3.2 Fidelity of Simulation Monitoring

The research worker using the console should be provided with an indication of the existing simulation fidelity (e.g. iteration rate, math model complexity, etc.). It is possible to display information on a CRT defining which subsystems of the simulation are degraded and currently inserted. Further, it is possible to use the CRT with, for example, a light pen, to insert required program or parameter status changes.

The "hierarchy" method of insertion and display of changes should be used. The CRT display would show first an index page, from which the simulation system to be affected would be chosen. The display would then change to show the system areas which could be changed, and the research worker would choose the required area. Finally, the display would show the degradation possibilities available in that simulation area, and any degradation, when selected, would be added to the list of existing degradations. The display could be switched to show this list at any time, thus providing confirmation to the research worker.

It is possible to use the hierarchy method to display details of a particular math model. This approach, however, requires large amounts of computer storage.

A more efficient approach to displaying math models would be to use an optical projection system and to place the written math models on film or slides. This approach would considerably decrease the requirement for computer storage of display data, and additionally would allow the nested Booleans to be identified, by, for example, different color or different typescript. The various stages of definition hierarchy would cause film or slide projection data to appear, and the next selections could be made by, for example, line number, until the math model level was reached. The optical projection system cannot, however, identify the status of the Booleans within the equations or whether sections of the math model are active or inactive.

This disadvantage could be eliminated by use of a ported CRT. The display could then appear by special projection on the rear of the faceplate, and the CRT could be caused to delete, or provide parentheses around, those sections of math model which were not active, under computer control. The research worker who wished to know the math model status of system would, therefore, be able to select the system via the selection hierarchy, and both slide or film projection and CRT modification would combine to identify the current status. The computer could be required to maintain a status list, which in this case would be a list of activated control Booleans rather than a list of existing degradations and, as before, this list would be available for access by the research worker.

It may be seen that the suggested method allows changes to be made at any time; however, it is strongly suggested that unless the results of a change in fidelity of simulation are known, the changes should be made only when the simulator is either frozen or reset.

The discussion has so far been limited to a single CRT display controlling one simulated aircraft. For the UPTRSS, using four simulated aircraft at the same time, the most desirable solution is to provide four CRT displays. The application defined in this section requires only alphanumeric CRT capability, and because such displays are relatively inexpensive and can be operated from a single set of interfacing electronics, it is recommended that four separate displays be used.

The CRT displays could also be used to give cross-country or approach information, monitoring graphically the flight path of each of the four simulators.

4.2.2 T-37 Instructor's Console

A discussion of the instrumentation of pilot/instructor locations for the T-37 has been given in Section 2. It may be recalled that the recommendation therein was that the instructor be located in the normal right-hand seat. In addition, however, an instructor's console could be provided with the repeaters of the aircraft cockpit instruments, and could be located external to the trainer on the research mezzanine. Such location is consistent with that used in most flight simulators, and furthermore is consistent with the recommendation for the T-38 trainers, as will be described later. The provision of an external instructor console equipped with repeaters of the T-37 cockpit instruments permits a baseline to be drawn for evaluation of more advanced instructor facilities based on different types of modern and more sophisticated hardware devices.

The possibility of including in the T-37 cockpit a small CRT display and a small keyboard to be used by the instructor for malfunction insertion or other purposes is discussed in Section 4.4.

4.2.3 T-38 Instructor's Console

In comparison with the T-37 aircraft there are fewer advantages to providing a second seat for the instructor in the simulated T-38 cockpits. As discussed in Section 2, since the trainee is not able to see either the instructor or the instructors instrumentation, it becomes possible to consider the feasibility of installing advanced control and training evaluation equipment at the cockpit second seat. Also discussed in Section 2 is a much simpler alternate arrangement whereby no instructor cockpit is provided. A folding jump seat adjacent to the pilot cabin can be installed for preflight briefing. The utility of such a seat may be severely limited, however, by the visual system configurations around the T-38 simulator cockpit.

Apart from the differences stated above, the facilities and equipment provided for the T-38 instructor should resemble those provided for the T-37 instructors.

4.3 MALFUNCTION INSERTION

Conventional simulator instructor facilities permit the insertion into the system of certain predefined malfunctions to increase the training task complexity for the student. It is highly likely that malfunction insertion techniques should be the subject of research at the UPTRSS. Facilities corresponding to those normally found at an instructor station should, therefore, be provided for both the T-37 and T-38 instructors.

Malfunction insertion by an instructor actually seated in the T-37 cockpit presents a problem, since the instructor is in full view of the trainee, who may become aware of any unusual instructor activities. In an extreme case, it could be possible for an experienced trainee to invalidate research results by being able to predict instructor actions. To circumvent this situation, a series of dummy controls could be provided which, if operated at random intervals, would camouflage the conventional actual malfunction control operations.

For display of malfunction status or, indeed, of aircraft status, a small alphanumeric CRT could be positioned in the cockpit facing towards the instructor and away from the trainee. This CRT display could be programmed to display to the instructor the required information. It might also be possible to project such CRT information onto some surface, for example a windscreen, with a very narrow field of view which excluded the trainee.

Malfunction insertion at the external instructor console should probably be accomplished by simple operation of one of a series of indentified switch lights. Other malfunction insertion methods are available which relate the switch lights to a slide-projected presentation of the aircraft system on the computer control. Such methods are more suitable to selection from a very large number of available malfunctions and would not be required for a relatively simple aircraft such as the T-37.

The conventional instructor instrumentation described above provides a basis for comparison with more advanced instructor equipment. Since realism in the T-37 cockpit cannot be maintained if such equipment is situated in the cockpit, it becomes necessary to provide a second external instructor console which embodies the more modern equipment. It is expected that the equipment most likely to be compared against conventional instrumentation will be the CRT display.

The CRT display provided for the simulator operator or instructor fulfills, broadly speaking, the same function as that provided at the research console. Whereas the CRT display at the research console provides information relevant to the research status and the instructor or trainee activities, the information presented at the instructor-operator CRT could provide information relating to only the individual exercise for trainee status.

It should be possible, under software control, to allocate either the CRT or conventional console to each of the T-37 cockpits in any manner – that is, both cockpits operating from one console, or one cockpit operating from each console, or one cockpit operating into both consoles. It is further desirable that some tie-up should be possible between the T-37 side of the research facility and the T-38 side of the research facility. This would permit the abilities of instructors, using either conventional or advanced consoles, to be evaluated when operating one, two, or up to four separate trainees.

4.4 PERIPHERAL HARD-COPY OUTPUTS

The primary task of the research computer, as mentioned in previous sections, is that of data gathering and analysis. The research computer also has the task of accepting inputs from and providing outputs to the research console. Since the research computer contains both the data generated by the research console and the data called under research computer program control from the simulator computers, the research computer is ideally suited to the task of providing to some peripheral output device or devices a "hard-copy" record. For record-keeping purposes it is essential that this output provide the status of the research facility simulators to which any raw or processed data applies. The desired result could be achieved by providing programs for the hard-copy output device to produce an identifying record whenever any of the research parameter controls are operated. It is also likely that operation of controls selecting particular preprogrammed exercises should also cause an identifying hard-copy record to be printed. It is considered that control settings or selections at the operator console will not need to be recorded since these settings will be primarily influenced or even defined by the preprogrammed exercise. Hard-copy results would certainly be required for the analysis of advanced training results and techniques. (See Section 11.)

Several types of hard-copy device suitable for the UPTRSS are available. If it is necessary to record only research parameter control settings as they occur in sequence, then a teleprinter output device, printing one character at a time at a rate of approximately 10 characters per second, should provide sufficient output speed. However, teleprinters are notoriously unreliable even though recent developments have tended to improve their reliability considerably. Teleprinters are also not usually located close to work areas because of their high noise level. They are, however, relatively inexpensive.

Higher output speeds may be obtained by use of a line printer. Line printers print one complete line (usually between 80 and 140 characters wide) at speeds ranging from 100 lines per minute to over 1,300 lines per minute. Line printers require regular maintenance and furthermore they are expensive to purchase. They are, however, usually enclosed in well sealed, soundproof cases.

A recent development in hard-copy output equipment has been the CRT line printer. In such devices the output signals are converted into character form in an electronic character generator and output onto a precision CRT. The output medium is photosensitive paper passing across the faceplate of the precision CRT. Although the output is generated character by character, this is performed at electronic speeds, and to the observer it appears that the output is being generated as complete lines of information. Similar devices exist in which the output appears on a matrix of very thin wires. The heating of the wires produces the required printed output on thermosensitive paper.

Printers of this type are generally much smaller than conventional electromechanical line printers (they are usually desk-mounted rather than full-standing) and since the mechanical portion is restricted to the appropriate paper feed, they consume far less power. The line width is usually between 40 and 80 characters. The absence of the electromechanical printing makes devices of this type very quiet and more suitable to an office atmosphere. The major disadvantage is, however, that the photosensitive or thermosensitive paper is considerably more expensive to purchase than conventional teleprinter or line printer paper, and is furthermore subject to aging unless very carefully preserved.

For the purposes of the UPTRSS, the CRT line printer would appear to possess definite advantages, notably in size and silence of operation. These attributes would allow the printer to be located very close to the research console without inconvenience to the operators. In the absence of a requirement for high recording speed, a line printer capable of approximately 250 lines per minute would be more than adequate.

4.5 DIGITAL PLOTTING CAPABILITY

In order to monitor and, where necessary, record the flight path of the simulated aircraft, it is necessary to provide the research area with some device capable of displaying graphical information. Several different types of device exist which could provide an output of this type.

One possibility would be to provide a conventional analog x-y recorder. The map information for these recorders is provided either by directly attaching an aeronautical chart to the front face of the recorder or by back projection of a similar chart using a high-quality projector and

slide. The ground track information in both cases is marked on the front face of the recorder by one or more moving carriages and pens. Recorders of this type suffer from several serious disadvantages, including lack of absolute accuracy, pen response characteristics (a function of the servo response characteristics), and requirements for frequent maintenance in order to preserve the desirable recording qualities. Furthermore, the recorder simply plots flight path information and any tabulations to be annexed must be provided by hand. (Recorders which plot the position as a series of alphanumeric symbols are available and such recorders can provide a limited editing capability. The capability for editing is, however, usually limited because of shortcomings in servo positioning accuracy.)

For interfacing with a digital computer, a digital incremental plotter is a more appropriate instrument and is now in widespread use. Digital incremental plotters are of two types, cylindrical plotters and flatbed plotters. The configuration has little effect on the basic operating principle. Flatbed plotters closely resemble analog x-y recorders, but the carriage and pen, instead of being positioned by analog servos, are driven by stepper motors controlled directly by the digital computer. The computer keeps track of the number of pulses output to the plotter and is therefore able to calculate the number of pulses necessary to output in order to restore the carriage and pen to their zero or nominal positions. The cylindrical plotter operation is similar except that there is no carriage movement, the y direction of paper movement being obtained by rotating a drum around which the recording paper is wrapped. Digital incremental plotters are available which will plot over an area 30 inches square with an incremental stepping size as small as 0.005 inches. Cylindrical plotters are available for roll paper widths of up to 36 inches and similar stepping sizes to flatbed plotters.

The advantages of digital incremental plotters over analog x-y recorders are numerous. First, their absolute accuracy is considerably higher, particularly with respect to repositioning to an absolute point. Second, since the pen may be moved over a small area with a positioning accuracy of 0.005 inches under pulse train control from the computer, alphanumeric character writing becomes simple, under the control of a software package in the digital computer provided specifically for that purpose. Output records may therefore be produced, with the editing information provided under computer software control. Third, incremental plotters require less maintenance than x-y recorders.

A large-screen CRT display may also be used for monitoring the flight path of the simulated aircraft. The method of depicting the information on the face of the CRT is similar to that used for a digital incremental plotter, and has many of the same advantages, such as the ability to present annotating information. It is expected that a large, flat-faced CRT (approximately 20 to 30 inches in diameter) would be used.

For obtaining a permanent record, several possibilities exist. One possibility is to drive a digital incremental plotter with the same information. This, however, is expensive because of the multiplicity of hardware. A second possibility is to photograph the face of the CRT at intervals using a Polaroid or other type of camera. This method has advantages for producing an immediate record, but a small photograph would not seem to provide sufficiently good output for critical evaluation at a research facility. A final alternative is to utilize hard-copy CRT equipment — i.e., equipment capable of direct printing from a CRT presentation onto photosensitive paper placed in contact with the surface of the CRT. A special precision CRT is required for this purpose. Several versions of such a CRT hard-copy output device have recently been developed and, if a CRT is used for monitoring and no other hard-copy output device is envisioned, such a printer would provide an adequate output. It should, however, be remembered that the record, being photosensitive, is subject to deterioration with age.

4.6 DATA ANALYSIS

An example of data analysis for the research facility might be as follows:

1) Correlation, comparison and tabulation of the output applying to one exercise or sequence of exercises.

2) Correlation and comparison of the results of an exercise or sequence of exercises with a previous exercise or sequence of exercises.

These examples are illustrative of two possible phases of operation. In the first type of analysis only the results appropriate to the most recent or current research would be available in the computer, and the purpose of performing the analysis would be principally to provide immediate feedback to the research workers, thus enabling negative trends in the research to be detected as soon as possible This would be accomplished in an on-line mode. By this means, abortive work could be terminated immediately, whereas if the results were analyzed off-line (e.g., by overnight computer run) the trend in the research might not be evident until the program of work had been completed.

The second type of data analysis, that of comparing the results from the present research program with those of previous research programs, will most probably require use of the research computer as a general-purpose data processor. This will be an off-line function, during which all input from and output to the simulator computers will be absent.

It is expected that by a process of selection and refinement the research staff will evolve a listing of the parameters which define the

required research results for a particular exercise. These results will be dumped onto magnetic tape in a prearranged format, and the tape will be used subsequently as the data source from which comparisons of the results with other research are made (see Figure 56).

During results analysis, therefore, the data appropriate to present and past research will be loaded into the computer from magnetic tape. Other magnetic tapes will be used for loading of analysis programs. The large-capacity disc memory (see Figure 56) will be used both as bulk storage for the analysis data loaded from magnetic tape and as an intermediate results storage buffer, if the analyzed results output rate exceeded the capacity of the output medium. The data should probably be output onto a hard-copy printer. However, dumping of data onto magnetic tape for printing at a more convenient time could be contemplated.

Control of off-line data analysis would be performed from the computer control panel or console (ground level, Figure 56) or from a control teletypewriter (at ground or mezzanine level) by means of suitable software. The data analysis could also be controlled from the research console keyboard, in which case the associated CRT display (if provided) could be used for display of computer status messages. One disadvantage to this proposal is that the CRT display, unlike the teletypewriter, does not produce hard-copy record of the control functions used. Another disadvantage is that the operator, while controlling the analysis, needs to observe correct functioning of peripherals (such as magnetic tape units) in response to control functions, and may also need to operate the computer control panel but will be remote from the equipments. However, once the analysis in under way, occasional observation of correct hard-copy printer operation is all that is necessary.

The best recommendation would seem to be that if standard software permitting data processing control from peripherals is available, then solely on grounds of versatility this software should be extended to permit control from the research console. If, in the final layout, the location of the console is such that this control is not considered feasible, then the provision is still useful since it will permit the research console keyboard, CRT, and computer to be interactively connected in a way which may not be provided under the standard simulator operating mode.

4.7 OPERATOR/TRAINEE RATIO

The number of research workers who are required to operate the UPTRSS will depend on the modes of operation under which research will be carried out. Section 4.1 delineates four possible modes of operation, and it may be assumed that numerous other modes will be used when the UPTRSS has been constructed. In designing the research facilities, therefore, it is necessary to consider the worst-case requirement for number of research staff.

The worst case occurs when the four cockpits are being operated on four separate and unconnected programs of research work. For example, a low-level visual problem, a motion system problem, an adaptive training problem, and a malfunction insertion method problem could be the subjects of study at one time. If this were the case, then it would be unrealistic to consider that one research worker could divide his time between and supervise four such unrelated areas of research. It is more likely that four research workers, one working on each problem, would be present.

Provision of fewer than four separate operator facilities, therefore, would necessitate some degree of facility time-sharing between the research workers. It is considered that the possibility of confusion and misinterpretation that could result from such time-sharing outweighs the extra cost incurred by purchasing additional facilities identical to those already designed. The recommendation is, therefore, that identical facilities for four research workers should be provided.

During the course of research, hard-copy output will be provided on such devices as line printer and digital plotter. These devices are under computer control and, furthermore, for only one research program, are likely to demand a very small proportion of research computer time. Even for four research programs operating concurrently, the demanded computer time will be small.

Since the hard-copy devices are under computer control there is no question of confusion or misunderstanding due to human intervention. It is feasible, therefore, to output all necessary alphanumeric data serially as required on the line printer, preceding the data with an identifying symbol. For the digital plotter, the repositioning accuracy would allow four separate graphical outputs (for a cylindrical plotter) or four overlay graphical outputs (for a flatbed plotter) to be output and plotted in sequence so as to produce the four required outputs at the same time.

4.8 INTERCOM FACILITIES

The research facility should also be provided with intercom facilities which allow communication, either individually or by selected groups, with both instructors and trainees. It is expected that the research staff will be unlikely to communicate directly with the trainees during training exercises; however, a facility would seem necessary to permit simultaneous communication with instructors or trainees prior to or during an exercise. The intercom facilities should be such as to allow the research staff to eavesdrop on and record on magnetic tape conversations between instructors and trainees, since such conversations provide a valuable clue to the effectiveness of the training method in use. The research staff should also be able to listen to any prerecorded audio messages (such as may be provided for navigation purposes).

For debriefing and analysis purposes, it would seem desirable to record conversations between appropriate instructors and trainees. Initial assessment would seem to indicate that a recorder with four channels, capable of recording continuously up to one hour simultaneously on the four separate channels, would be adequate for the research facility.

5. COMPUTATION FUNCTION

The computation function for the UPTRSS will be performed by a computer complex, and this complex will be connected to the four cockpits and associated instructor-operator facilities by means of an interface system. This section of the report analyzes the requirements for the UPTRSS computer complex and interface system.

Although the UPTRSS computer complex could conceivably be analog, hybrid, or digital in nature, for a variety of reasons the first two approaches were quickly rejected for the research facility. Analog and hybrid computers excel in many applications, but for a large facility that demands program flexibility they would represent a severe handicap. The requirements for modifying the characteristics of the trainer mathematical models and for providing the capability for extensive data comparison and analysis both dictate the use of a digital computer.

The total computational system envisaged for UPTRSS can be considered as consisting of three main blocks (see Figure 12):

1) The digital computer, where all the processing is done

2) The real-time interface, which provides communication between the digital computer and the four cockpits

3) The peripheral equipment which allows the operator to communicate with the digital computer.

Each of these three blocks is discussed separately in the paragraphs that follow.

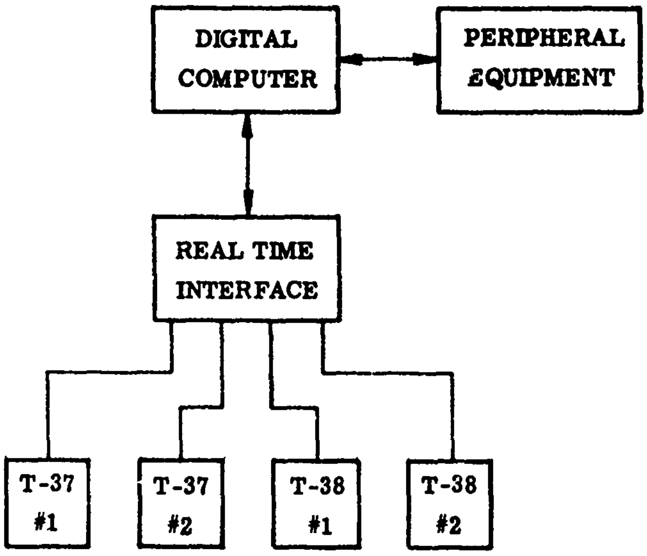


Figure 12 UPTRSS COMPUTATION SYSTEM

5.1 CONFIGURATION REQUIREMENTS

The UPTRSS computer complex will consist of:

1) One or more central processors

2) Memory for program and data storage

3) Input/output channels or processors

These elements may be organized in many different ways. To indicate the range of possible organization, three fundamentally different configurations are discussed.

5.1.1 Single-Processor Configuration

This configuration is illustrated in Figure 13 and would consist of a single central processor and single input/output processor. The central processor would be time-shared between the four cockpits so that the four trainers would be able to fly independent real-time missions simultaneously with no interference. Such operation would require the central processor to have sufficient computational speed to execute all programs in real time. Because instructions are executed sequentially, the processing speed of the central processor must be such that any single trainer would require less than one-quarter of the available processing time (spare time must be available for data analysis). The same requirement would apply to the I/O processor -- i.e., the I/O transfer rate must be sufficient to provide for all data transfers in real time.

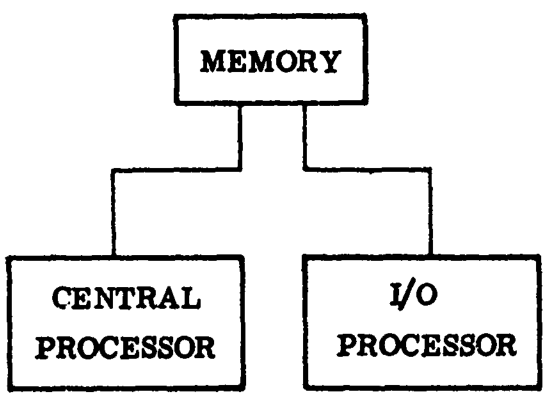


Figure 13 SINGLE-PROCESSOR CONFIGURATION

5.1.2 Multiprocessor Configuration

A multiprocessor configuration (see Figure 14) would consist of two or more central processors (CPU's) sharing a common memory bank that is accessible by either processor. Each processor would also be provided with a bank of private memory accessible only by that individual CPU. Such an arrangement would allow the processors to operate in parallel on portions of the problem so that the effective processing speed of the complex would be greatly increased. The total program could be so structured as to allow each CPU to work on the programs and routines associated with one cockpit or, alternatively, to work on separate functional programs for all cockpits. For example, CPU No. 1 could execute all flight and engine programs while CPU No. 2 processed communication and navigation programs. A functional arrangement (e.g., all flight equations processed by one CPU) is very undesirable from an operational viewpoint because failure of any processor would mean failure of all trainers. From an economic viewpoint it might appear advantageous to utilize the functional arrangement to enable a single program to be stored in private memory and utilized four times, thereby conserving memory. However, it will be demonstrated in Section 7 that shared routines would not be the most satisfactory approach for UPTRSS programming. The conclusion is that if a multiprocessor configuration is selected for the UPTRSS the programs should be assigned to the various CPU's by cockpit rather than by function.

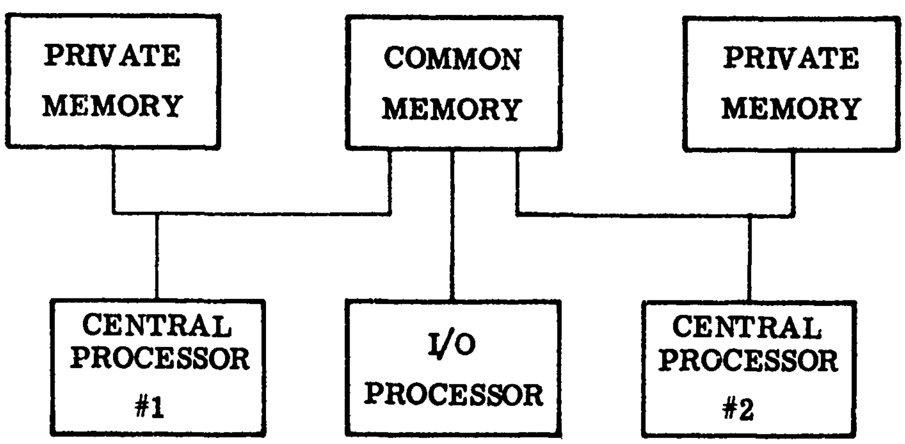


Figure 14 MULTIPROCESSOR CONFIGURATION

5.1.3 Multicomputer Configuration

This configuration is shown in Figure 15 and consists of four separate and independent central processors and separate I/O processors, each working on separate and independent memory units. Such an arrangement allocates a separate computer to each of the four trainer cockpits, permits no shared memory, and limits communication between computers to I/O channels. It is obvious that such a configuration would allow each of the trainers to operate entirely independently of any of the others and would mean that equipment failures on one computer would have no effect on the other operating simulators. This operational advantage is offset, however, by the lack of flexibility of the multicomputer arrangement for research applications because of the inability to directly access common data blocks.

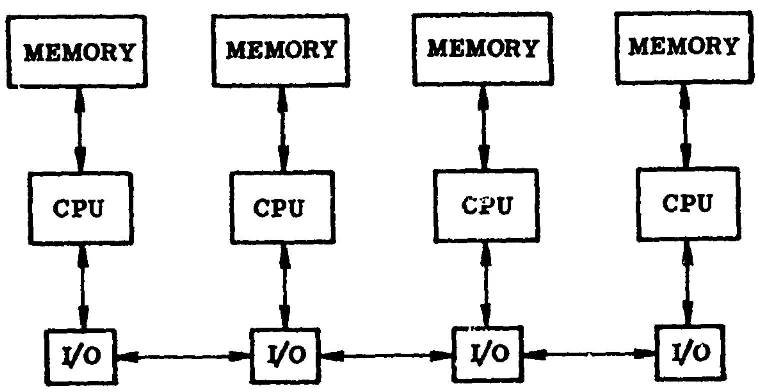


Figure 15 MULTICOMPUTER CONFIGURATION

5.1.4 Comparison of Configurations

Three possible computer configurations have been described and some advantages and disadvantages of each have been cited. Figure 16 compares the various technical features and capabilities of the three configurations.

The advantages and disadvantages listed in the figure are biased towards the UPTRSS application and stress operational considerations for the research facility. The same considerations would not apply to other applications of a four-trainer complex. For example, if the complex were to be utilized for training purposes only (no research requirement), then the major disadvantage of the multicomputer configuration would disappear and this

Configuration	Advantages	Disadvantages
Single Processor	Programming ease	Every cockpit dependent upon the single computer
	Much simpler executive	
	Flexibility of program and memory assignment for research applications	
Multiprocessor	Permits partial use of the research facility while one CPU is inoperative or while the programs for one trainer are being modified	Executive becomes more complex
		Flexibility for research reduced compared to single processor
Multicomputer	Each cockpit can be checked and debugged without affecting operation of others	Flexibility for control and comparative analysis greatly reduced
		Requires more hardware for the total system

Figure 16 COMPARISON OF COMPUTER CONFIGURATIONS

configuration would appear to be most attractive. However, because of the flexibility required for evaluating many modes of operation and for analyzing different aspects of trainer capability, the single-processor computer configuration is considered to be the most desirable for the UPTRSS.

The economic feasibility of obtaining a single processor of sufficient capacity for the four-cockpit research facility has not yet been discussed. It will be shown in the following section that the only computers available today that are capable of handling the task are extremely expensive. Thus, if budget

considerations exclude the purchase of a single processor, then the next most attractive solution to the UPTRSS task would be a multiprocessor computer configuration. The multiprocessor computer would be somewhat more difficult to program and to modify, but the use of shared data memory would permit considerable flexibility for comparative data analysis. A multiprocessor configuration is also advantageous in that it would enable an abbreviated facility (e.g., two cockpits and one CPU) to be procured initially. The facility could later be expanded with the addition of more trainers and more processors as required.

5.2 PROCESSOR REQUIREMENTS

5.2.1 Processing Speed

In order to determine the processing speed required by the digital computer, it is necessary to analyze the anticipated computer loading for the task. Figures 17 and 18 show an analysis of the computing speed required. The first figure provides a breakdown of the various aircraft systems and operational programs associated with Simulator No. 1. For each of these systems and programs an anticipated computer loading is given. The figures are based upon previous Link experience with simulators of this type and have been scaled for "maximum" fidelity of each system. That is, the figures have been adjusted to provide for the storage and processing of mathematical models that are more detailed and complete than required for "satisfactory" simulation, and this was done to permit flexibility in the experimental selection of degraded models to enable optimum models for each system to be determined.

The figures for processing speed are given in terms of number of instructions per second for the various systems. It might be expected that these numbers would vary somewhat dependent upon the computer selected. That is, the processing requirements for any particular program would depend upon the particular characteristics of the digital computer used. However, experience has shown that the computer dependence is quite small and that to achieve the same results the variation in processing speed between computers is slight. Thus the figures shown can be assumed to apply, with some degree of confidence, to any random-access digital computer. When the numbers are totaled, the computational requirement for Simulator No. 1 is 155, 000 instructions per second. As an example of how this number compares with the processing requirements for existing flight simulators, it should be noted that a 707 flight simulator requires approximately 220, 000 instructions per second, a 747 flight simulator about 310, 000 instructions per second, an F-4E weapon system trainer about 400, 000 instructions per second, and an F-111A mission simulator about 450, 000 instructions per second. The high figures for the latter two simulators reflect the large amount of tactics simulation that is provided with military trainers.

System	Number of Instructions Required to be Executed per Second	Number of Words of Memory Required
Flight	75, 000	8, 000
Engines	25, 000	3, 000
Accessories	15, 000	5, 000
Navigation/Communication	20, 000	5, 000
Visual	20, 000	5, 000
Total	155, 000	26, 000

Figure 17 ESTIMATED COMPUTER LOADING FOR T-37 NO. 1

	Number of Instructions Required to be Executed per Second	Number of Words of Memory Required
Simulator No. 1 (T-37 No. 1)	155, 000	26, 000
Simulator No. 2 (T-37 No. 2)	155, 000	26, 000
Simulator No. 3 (T-38 No. 1)	175, 000	30, 000
Simulator No. 4 (T-38 No. 2)	175, 000	30, 000
Research Processing	300, 000	20, 000
Spare	200, 000	25, 000
Total	1, 160, 000	157, 000

Figure 18 ESTIMATED COMPUTER LOADING FOR UPTRSS COMPLEX

A similar type of loading analysis was carried out for the other trainers of the UPTRSS and the results are shown in Figure 18, where the totals for all four cockpits and for research processing are provided. Research processing consists of all provisions for automatic scoring and performance evaluation plus additional on-line data processing that may be desirable. The processing requirements for these functions are estimates only and have been scaled to permit a considerable amount of research processing. In addition, approximately 20% spare processing capacity has been included.

The totals for the four cockpits, the research processing, and the spare capacity indicate that the processing speed required for the UPTRSS is approximately 1.2 million instructions per second. This is a considerable computational load and is beyond the capacity of all but the most powerful (and expensive) of present-day computers.

Figure 19 presents a tabulation of the pertinent characteristics (cost and processing speed) of the most powerful computers presently available. The figures were extracted from the Adams Associates survey for 1968 and are approximate only. In particular the cost figures were derived by multiplying the average monthly rental by a factor of 40 rather than by attempting to cost out a specific complex. This approach was selected because detailed pricing information on large complexes is difficult to obtain except by extended negotiations with the computer manufacturer and also because the approximate cost figures for most of the computers is so large that further investigation was not considered to be warranted at this time. The processing speeds shown in Figure 19 were obtained by multiplying the total computer add time by a factor of 1.3 (to obtain the approximate average instruction execution time), and then taking the reciprocal of this figure to obtain the processing speed in instructions per second. The total add time is defined as the time required to acquire from memory and execute one add instruction using all features such as: overlapped memory banks, instruction look-ahead and parallel execution. Experience with simulator program has shown that the factor of 1.3 provides a fairly accurate conversion from add time to average instruction execution time.

Figure 19 indicates that all of the currently available computers that are capable of handling the UPTRSS problem with a single processor are very expensive. The only computers that would appear to approach economic justification for the task would be the Univac 494 and the B6500. By contrast the last entry in the table shows the equivalent characteristics of a three-CPU SDS Sigma 5 computer. It is apparent that of those computers listed, the multiprocessor Sigma 5 is economically far more suitable to the UPTRSS task than a single large processor.

The Sigma 5 is not the only computer in its class that would be suitable, in a multiprocessor configuration, for the research facility. The Honeywell 632, the CDC 3500, the SDS Sigma 7, and the IBM 360/44 are other machines that would provide the required computing capacity with a two- or three-processor configuration.

Computer	Processing Speed (Millions of Instructions/Second)	Approximate Cost (Millions of Dollars)	Comments
CDC 7600	7.8	5.0	Ten-processor complex
IBM 360-90	4.3	6.0	
B8500	3.9	7.0	
CDC 6600	2.6	2.9	Ten-processor complex
B6500	1.9	1.7	
Philco 2000 Model 213	1.4	3.2	Four-processor complex
Philco 2000 Model 212	1.3	2.2	Four-processor complex
Univac 494	1.03	1.5	
Univac 1108 Model 11	1.03	2.4	
IBM 360-75	.975	3.2	
CDC 3800	.780	2.2	
Three CPU Sigma 5	1.2	1.0	

Figure 19 CHARACTERISTICS OF LARGE-SCALE COMPUTER COMPLEXES

5.2.2 Data Word Size

Many previous reports and studies have investigated word length from the point of view of computational accuracy and stability. These investigations have conclusively demonstrated that a 16-bit word length is adequate for most computed data but that quantities which are numerically integrated will require 24 to 30 binary bits to achieve the necessary accuracy within the integration time frame.

This required accuracy could be achieved by employing a 32-bit word length computer, a 24-bit word length computer that provides double-precision computation for the few quantities requiring more than 24 bits of accuracy, or a 16-bit computer that has double-precision capability for integrated values. The memory penalty associated with the use of double-precision computation in a 16-bit computer is negligible (on the order of 100 additional data words), while the time penalty is small, particularly if the computer offers a hardware double-precision capability. In general these small penalties are more than offset by the fact that 16-bit memory is much less expensive than 24- or 30-bit memory and hence there is sound economic justification for selecting 16-bit computers for small simulation problems.

However, for large simulation complexes, other considerations weigh heavily against short-word-length computers:

1) Addressing Problems - Memory words used for instructions must be organized into several sections: the op-code, the indexing and indirect addressing bits, and the address. A computer that uses a short-word-length memory has very few bits available for the address portion of the word, and this means that only a small amount of memory can be directly addressed. For a 16-bit computer, 9 or 10 bits are all that can be allotted to the address field, and this limits the amount of directly addressable memory to 512 or 1,024 words. All other memory must be addressed by indexing (usually with respect to a floating index register) or by indirect addressing. In most cases these addressing schemes have the effect of extending the instruction execution time and slowing down the processor. This problem is not critical for small simulators because a single 16-bit processor will have ample processing speed. However, as previously discussed, the UPTRSS problem would require a multiprocessor 16-bit computer with a great deal of memory, and for this configuration the addressing problems inherent in a 16-bit word length would complicate machine operation. It should be noted that some of the problems mentioned can be minimized through appropriate arrangement of the simulation programs. For example, if functional organization were acceptable, indexing would be required for this purpose, and the same index register would give the flexibility of addressing the entire memory of a 16-bit machine.

2) Programming Complications - Because of the relatively few bits available for addressing and for designating op-codes, short-word-length computers are more difficult to program. This is especially true for 16-bit computers when used on a multiprocessor complex. The requirements for real-time simulation compound the difficulties because of the need to structure a large portion of the problem on a fixed time scale. For example, the repetition rate for any program containing integration routines must be carefully controlled, and yet the execution time for the routine will vary greatly depending upon the amount of indexing and indirect addressing required. In a multiprocessor complex the programs must be so structured as to minimize timing problems and avoid conflicts in accessing common memory.

3) Inefficient Use of Floating Point Data – Section 7 of this report points out the requirement for the use of a high-level compiler language (e.g., Fortran) on the UPTRSS. Compiler languages are available for short-word-length machines, but these compilers produce object code that treats data as floating-point numbers. While this object code can be run (by means of subroutines) on computers that do not have floating-point arithmetic units, such operation imposes a very large time penalty on the program. The UPTRSS computer should have a hardware floating-point capability. Although a few short-word-length computers have optional hardware floating-point modules, these machines treat all floating-point numbers as double-precision numbers (two words) and thus are very inefficient in the use of data words.

One can conclude, therefore, that a short-word-length computer would be undesirable for the UPTRSS application and that a computer with a word length of at least 24 bits should be specified.

5.2.3 Instruction Repertoire

The possibility of attempting to specify an "optimum" set of instructions for the UPTRSS computer was considered but rejected for the following reasons:

1) Opinions as to the desirability or worth of particular instructions are extremely subjective and dependent upon the experience of the individual programmer. Thus general agreement on the makeup of an optimum instruction set is almost impossible to obtain.

2) For obvious economic reasons the computer selected for the UPTRSS problem should be an off-the-shelf machine rather than a one-of-a-kind special design; therefore any attempt to specify a particular instruction set would be something of an exercise in futility.

However, it is feasible to describe certain types of instructions that would be desirable for the UPTRSS computer:

1) Fixed-Point Arithmetic Instructions – A complete set of fixed-point arithmetic instructions is required. These instructions should include add, subtract, multiply, and divide in both single and double precision format. A square root instruction is also very desirable for simulator applications.

2) Floating-Point Arithmetic Instructions – A set of floating-point arithmetic instructions is highly desirable. As previously mentioned, hardware floating-point capability will be required for efficient utilization of a (standard) high-level language compiler. Floating-point operations should include at least add, subtract, multiply, and divide instructions. The floating-point square root instruction is also desirable, as are instructions that enable format conversion from fixed to floating-point and floating to fixed-point numbers.

3) Logical Instructions - A set of logical, or decision-making, instructions is required. This set should include unconditional branch, conditional branch, compare and branch, and branch and store instructions. The conditional branch instructions should provide for several conditions - e.g., branch if a number is positive, branch if a number is negative, and branch if a number is zero. The compare and branch instructions should provide for comparison of a number with another number and should provide conditional branching dependent upon whether the first number was greater than, equal to, or less than the second.

4) Boolean Instructions - A set of Boolean operations is required. This set should include Boolean "and," "or," and "exclusive or" instructions. It would be desirable if Boolean instructions operated upon single bits rather than full words, and therefore bit addressing, at least between registers, is very desirable. Because of the large number of Boolean operations inherent in simulation problems, the capability of performing bit addressing between registers and memory is also very desirable because it would permit all Boolean (single bit) data to be packed into full words for storage within the computer. This capability would enhance handling of discrete outputs as discussed in Section 5.3.2.

5) Data Handling Instructions - A set of instructions must be provided that will enable the computer to transfer data between memory and CPU registers and also to input and output data through I/O channels. The set should include: single and double precision load and store instructions; shift instructions, including doubleword and circular shifts; and I/O block transfer instructions, with the block length selectable. If the computer has a word length 32 bits or greater, data handling instructions should permit manipulation of halfwords and bytes as well as full words.

5.2.4 Total Memory Storage Requirements

The computer loading estimates provided in Figure 18 indicated that approximately 160,000 words of memory storage would be required for the UPTRSS. These figures included estimates for both programs and data for the four trainers and for research processing and also included approximately 20% spare memory for expansion.

It should be noted that the estimates for the four trainers did not assume shared programs between cockpits. As discussed elsewhere, programs could be shared in a functional manner (both T-37's use same flight programs, etc.), and this arrangement would reduce the total storage requirements somewhat. However, the requirement to use the UPTRSS to investigate optimum modeling by degrading specific programs would virtually eliminate any advantage to be gained by program sharing. For example, it would be desirable to fly both T-37's simultaneously, one with

degraded flight equations and one with the complete equations, to compare trainee response. Under these conditions the two cockpits could not share flight equations without unduly complicated math models and programs.

For this reason the loading estimates are added individually and the total figure of 160K words represents the estimated requirement for directly accessible computer memory.

In addition a considerable amount of bulk storage memory would be desirable for use of comparative programs, stored maneuvers, CRT displays, and automatic scoring exercises. These programs could be contained in a fast-access bulk-storage medium such as a rapid-access disc and transferred into main memory as required.

5.2.5 Provisions for Adaptability and Growth Capability

Because of the unspecified nature of the research operation and because of the flexibility required for modifying and updating programs, it is essential that the computer delivered with the UPTRSS have capability for future growth. It must be possible to expand the computer, both in terms of processing speed and in terms of available memory. The requirement for future expansion dictates that the computer complex be modular in structure so that additional processors and additional memory may be conveniently added at some future date.

5.3 COMPUTER INTERFACE EQUIPMENT

In order to effectively transfer information between the digital environment of the computer and the analog environment of the simulator, interface equipment is required. The computer interface equipment must be bidirectional – that is, it must transfer information into as well as out of the computer. For output operations, the computer interface equipment performs three major functions:

1) Accepts time-multiplexed (sequential) outputs from the computer. These outputs are generally byte-serial or word-serial and are transmitted on a single set of data lines. The computer interface equipment, in order to properly accept these outputs, incorporates a controller with counters, logic, and gating for steering each output word (or byte) to its correct destination.

2) Converts each output into the form best suited to its ultimate use. This conversion may be as simple as changing voltage levels or current drive capability or it may involve digital-to-analog conversion.

3) Stores the outputs in parallel fashion so as to provide continuous (non-multiplexed) outputs on separate lines. This storage may take

the form of flip-flops for discrete digital outputs or sample-and-hold amplifiers for analog outputs.

For input operations, the computer interface equipment performs three similar but slightly different functions:

1) Periodically samples continuously available inputs which are provided on separate lines

2) Converts each input to digital form at levels suitable for transfer to the computer

3) Transmits the input data to the computer in a byte-serial or word-serial (time-multiplexed) fashion.

For inputs as well as outputs the computer interface equipment controller provides the necessary bookkeeping to assure that data is properly routed.

5.3.1 Interface-Computer Side

As mentioned previously, the computer side of the interface operates in a time-multiplexed or serial mode. A considerable number of types of computer I/O channels are available. The nature of the I/O channel is one of the important parameters affecting the nature and performance of the computer interface equipment.

Computer I/O channels generally fall into one of two major classifications: single-word channels and block-transfer channels. The single word channels are unsuitable for applications such as the UPTRSS, which requires the exchange of large amounts of information between the computer and the interface equipment. These channels require the execution of an I/O instruction by the CPU for every word transferred. These instructions plus the bookkeeping instructions necessary to establish block limits and timing impose an undue burden on the CPU.

Block-transfer channels have the capability of automatically transferring large blocks of data after being initiated by a single set of instructions. A block-transfer type of I/O channel is essential to the UPTRSS in order to minimize I/O system demands on processor time.

The specific implementation of block-transfer I/O channels varies considerably, but the major characteristic of most such channels can be defined in terms of four parameters:

1) Cycle Stealing - A block transfer channel may or may not be a cycle stealer. A cycle-stealing channel is one which interrupts the CPU for a short period of time (generally one memory cycle) for each informa-

tion transfer. This usually results from the sharing of registers, arithmetic capabilities, or a common memory bus. Non-cycle-stealing channels are generally more expensive than the cycle-stealing type but, because they possess their own registers, control logic, and memory ports, are able to access memory in an overlapped fashion so as to minimize CPU time penalties. A non-cycle-stealing I/O channel is desirable for the UPTRSS to minimize CPU delays.

2) Word or Byte Orientation - Some block-transfer channels are word-oriented - i.e., a full word is transferred in parallel to or from the computer interface equipment. Other channels are byte-serial in that each word is subdivided into two or more bytes which are transmitted serially to or from the computer interface equipment. Often the byte-serial I/O channel is further limited in that only one byte is obtained from or stored in memory with every access. In such cases, the memory access requirements are increased and the data rates decreased as compared with channels which provide word assembly/disassembly in the I/O channel. For the UPTRSS a word-oriented channel is desirable since the control logic in the computer interface equipment is simplified. The improved data rates may or may not be of significance, depending on whether the actual data rates obtained with specific channels meet the requirements of the UPTRSS.

3) Multiplexing - Some block-transfer channels are multiplexed so that they can service two or more devices on an interlaced basis according to some priority scheme. Such channels usually incorporate separate range and address counters for each device interface. Each time access to core memory is gained, a word (or byte) of information is transferred to or from the highest-priority device requesting access and the appropriate range and address counters are modified. Nonmultiplexed channels are able to service only one device at a time. Once a block transfer is initiated, all other devices are locked out until the entire block of words has been transferred. A multiplexed I/O channel is generally desirable for servicing devices which are slow in comparison with the I/O channel data rates, whereas a nonmultiplexed I/O channel is adequate for a device which can operate at a rate approaching the I/O channel data rate. Since the computer interface equipment will incorporate analog-to-digital and digital-to-analog converters which are relatively slow, the multiplexed type of I/O channel is desirable.

4) Buffering - Some block-transfer channels are buffered so as to minimize timing problems. When a channel is not buffered, the device must generally respond to a core memory access within a specified time frame. In other words, the interface is synchronous. A buffered channel, on the other hand, provides an asynchronous interface in that the core memory and the device each operate in their own time frame while a buffer register provides storage from the time the data is available until the time that it is used. Whether or not a buffered channel is required

depends on the I/O timing and the distance of the device from the computer as well as other less important factors. Generally, for servicing computer interface equipment, a buffered channel is desirable but not essential.

5.3.2 Interface--Trainer Side

The trainer side of the computer interface equipment consists of a large number of parallel input and output channels each of which is suitable for its intended purpose. In general, the outputs assume steady-state values which are updated periodically by the computer. Some form of storage is required to maintain the values between updates. Inputs, on the other hand, are maintained and are sampled periodically by the computer interface equipment for transmission to the computer. The most common types of I/O channels are:

1) Discrete Inputs - These are generally obtained from switches, encoders, or other devices which are essentially discrete or digital in nature. Individual discrete signals or individual bits in digital words are generally grouped into words for transmission to the computer.

2) Discrete Outputs - These are signals which are used to drive lights, relays, and similar devices external to the computer. From the standpoint of interface equipment complexity and data rates it is desirable to group these outputs in the same way that discrete inputs are grouped, but since packing of outputs by the computer may impose a severe time penalty they are often output in the same form in which they are generated by the computer.

3) Analog Inputs - These are DC analog voltages, usually in the -10 VDC to +10 VDC range, which are sampled periodically and converted to digital form by an analog-to-digital converter for transmission to the computer.

4) Analog Outputs - These are DC analog voltages, usually in the range of -10 VDC to +10 VDC, which are updated periodically by a digital-to-analog converter which receives inputs from the computer. One technique employs sample-and-hold amplifiers which provide storage of the analog voltage between updates.

5) Synchro/Resolver Outputs - These are AC analog voltages, most often 400 hz, which are used to drive synchros and/or resolvers. These are often defined as part of the trainer peripheral equipment rather than the computer interface equipment and are driven by DC analog outputs in such cases. Direct digital-to-synchro converters are also available. The decision as to which to use is most often based on comparative costs since both provide adequate performance.

The division of the computer interface equipment into four or five types of I/O channels as described above is almost universal, since all trainers require a variety of types of I/O. Accordingly, the UPTRSS can be expected to require all of the above types of I/O channels. The special nature of the UPTRSS, however, dictates a further division of the problem. This requirement arises from the fact that the UPTRSS is a multicockpit facility.

When using a single computer complex (whether single processor or multiprocessor) to drive two or more cockpits, a decision must be made as to whether a single computer interface system should be used to drive all of the cockpits or a separate computer interface should be used for each cockpit. The main arguments favoring a single interface system are:

1) Flexibility - Where a single interface system is used to drive all (in this case four) cockpits, all spare inputs and outputs are available for assignment to any cockpit. This provides somewhat more flexibility than the situation existing when each cockpit has its own interface equipment, including spares.

2) Cost - A single interface system with a single controller is inherently less expensive than four separate interface systems.

On the other hand, arguments favoring the use of separate interface systems are:

1) Availability - When a single interface system is used for all cockpits, a failure in a critical area such as the controller, or the maintenance procedures for a failure in a less critical area can necessitate shutdown of all cockpits. On the other hand, if each interface system is independent of the others, a failure in one has no effect on the others and the trainer can operate at a reduced level.

2) Data Rates - In general, the use of separate computer interface systems coupled with a multiplexer I/O channel can significantly improve the data rates over those which can be achieved with a single computer interface.

Figure 20 illustrates the system configuration which is the most desirable technically. Some of the compromises discussed previously may of course be warranted for economic or other reasons. The suggested system consists of four separate linkage controllers each of which controls the operation of four I/O devices: analog outputs (AO) analog inputs (AI), discrete outputs (DO) and discrete inputs (DI). In addition, a fifth I/O device, the synchro/resolver driver (SRD), may be required if such devices are incorporated in the trainer (as they likely will be).

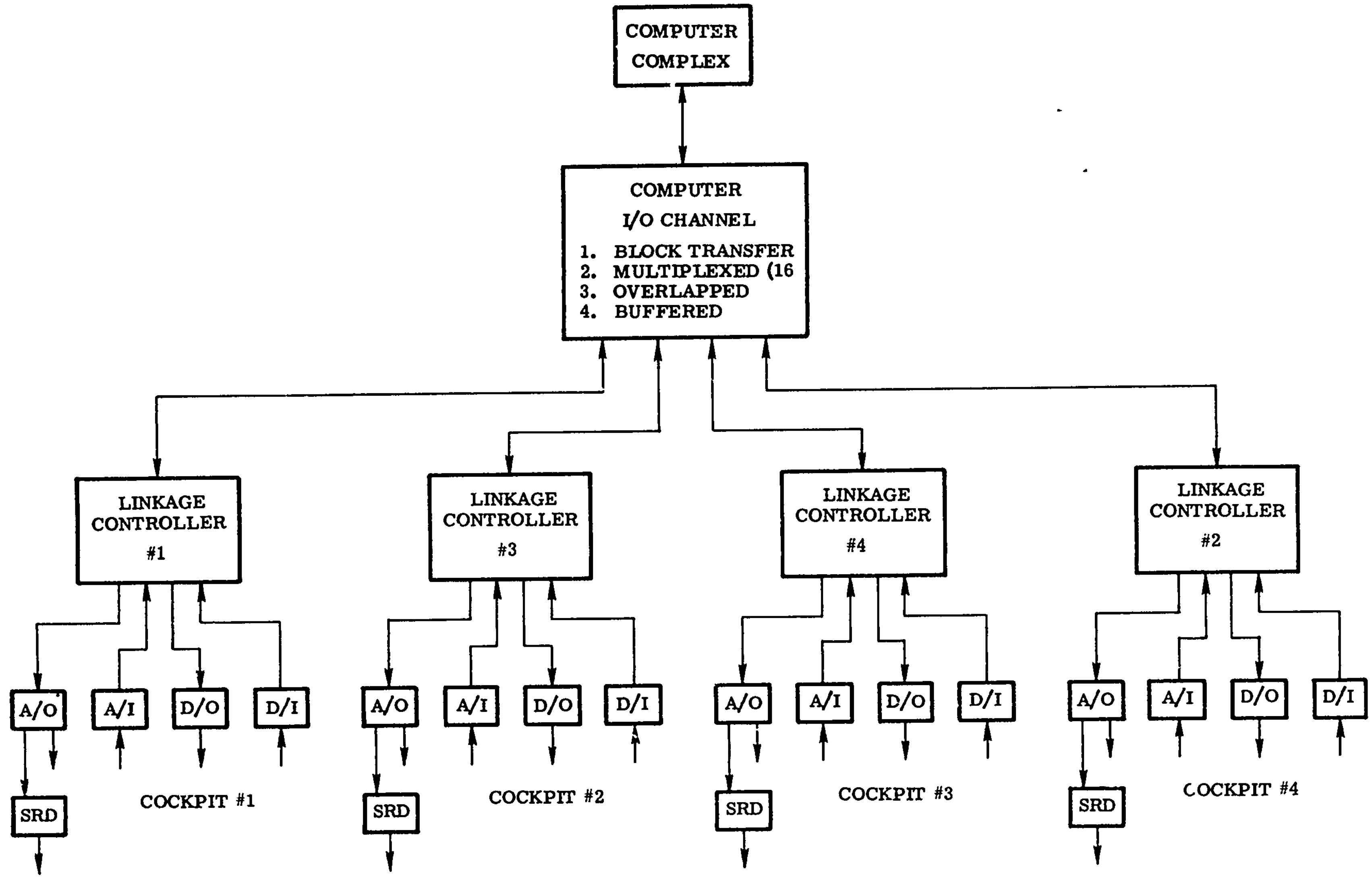


Figure 20 SUGGESTED UPTRSS COMPUTER INTERFACE EQUIPMENT

All four linkage controllers interface with a computer I/O channel which should be a buffered, multiplexed block transfer channel with an independent access path (port) to memory. Since each linkage controller would include four devices, it is necessary that the I/O channel be capable of servicing up to 16 devices, though not necessarily simultaneously. A capability of servicing four devices simultaneously would be desirable, however.

5.3.3 Input/Output Device Requirements

Because of the requirement for four cockpits, the UPTRSS will require a large number of inputs and outputs. The actual number of channels required will ultimately depend on the nature and extent of the instrumentation in the individual cockpits and the instructors' stations. Past experience has shown, however, that the approximate input/output counts can be fairly well established from the aircraft complexity and the intended functions of the simulator.

In the case of the UPTRSS, a considerable number of spare channels must be provided to allow for future expansion. Economic considerations dictate that the expansion capability be provided in a manner such as to achieve optimum tradeoff between initial cost and expansion cost. This can be best achieved by providing computer interface equipment with plug-in expansion capability wherein additional channel modules can be plugged into receptacles allocated and prewired for that purpose. In this way, the cost of the additional plug-in modules can be deferred until they are actually needed.

The anticipated I/O channel requirements are tabulated in Figure 21, along with recommended expansion capability. In conjunction with the requirement for plug-in expansion, it is important that the maximum data rate of the computer I/O channel be considered. The provision of plug-in expansion of the interface equipment is of no value unless the computer I/O channel can accommodate the additional I/O transfers required by the rates on the initial channels.

TYPE	ANTICIPATED REQUIREMENTS	PLUG-IN EXPANSION	TOTAL
Discrete Outputs	3000	1500	4500
Discrete Inputs	4000	2000	6000
Analog Outputs	600	300	900
Analog Inputs	300	150	450

Figure 21 UPTRSS INTERFACE REQUIREMENTS

The data rates of computer I/O channels are generally in excess of those required to service even a large interface system. Thus it is reasonable and economical to require that the computer and interface system be capable of serving all I/O channels at the rate of 20 samples per second. Many I/O channels can be served at lower rates but the requirement for 20 samples per second provides an added safety factor for expansion purposes.

The provision of four separate interface systems in conjunction with a multiplexed I/O channel will serve as added assurance that the required data rates can be met. Data conversion devices such as analog-to-digital and digital-to-analog converters are quite slow in comparison with the available data rates. If a single data path were used, it would be possible for these devices to tie up the I/O channel for sufficient periods of time to compromise the overall data rate. By multiplexing a number of these devices, the I/O channel can be used at more nearly its full potential.

Specific characteristics of the various I/O devices are discussed in the following paragraphs.

5.3.3.1 Discrete Inputs

The discrete input system should accept switch or encoder inputs on separate lines in a parallel fashion and should sample the lines for transmission to the computer in a word-serial or byte-serial fashion. The inputs should be at a comparatively high voltage level (e.g., 28 VDC) so as to improve noise rejection. Level converters should be used to reduce the input voltages to the appropriate level for the logic modules used in the interface system. A noise rejection of ± 10 VDC is desirable so as to avoid the requirement for special wiring considerations. This is important in view of the large number of wires required for discrete inputs.

5.3.3.2 Discrete Outputs

The discrete output system should provide solid-state switch closures (e.g., grounded-emitter transistor or the like) to ground for operating lights, relays, and other devices of a discrete nature. The discrete outputs should be capable of conducting at least 100 milliamperes and should withstand open-circuit voltages in excess of 30 VDC.

5.3.3.3 Analog Inputs

The analog input system should accept DC analog inputs in the range of -10 VDC to +10 VDC on separate wires and should sample and convert these to digital form for transmission to the computer in a word-serial or byte-serial fashion. The analog-to-digital converter should provide a resolution of at least 13 bits (12 bits plus sign) and should exhibit a noise-free accuracy of 10 bits.

5.3.3.4 Analog Outputs

The analog output system should provide DC analog voltages in the range of -10 VDC to +10 VDC on separate lines. The digital-to-analog converter should provide a resolution of at least 13 bits (12 bits plus sign) and should provide an accuracy of 0.1% on the output voltage referred to the digital word input to the converter. Where sample-and-hold amplifiers are used for output storage, the peak-to-peak value of the output ripple should be no greater than 10 millivolts.

5.3.3.5 Synchro Outputs

Where synchro instruments are to be driven by computer outputs, the overall accuracy of the synchro drive system should be ±0.5° when used with synchros having an accuracy of 6 minutes or better.

5.3.3.6 Converter Resolution and Accuracy

The requirement for 13 bit word length is dictated by the necessity to provide signals of sufficient resolution as well as conversion accuracy. Converter resolution is determined by the step size of the least significant bit. For example the least significant bit of a 10 bit converter defines one part in 1024 of the full scale number and the converter resolution is thus limited to one part in 1024. Converter accuracy on the other hand is a complex factor that is dependent upon component selection and system design as well as word length. The maximum theoretical converter accuracy is ±1/2 of the least significant bit; however, in practice the accuracy obtainable is considerably less than this and is on the order of ± the second or third least significant bit. Thus 10 bit converters are available which are accurate to 9 bits which is one part in 512 or approximately ± 0.2%.

Link has found from experience that 10 bit resolution and 9 bit accuracy are inadequate for many simulator conversions. For example synchro instruments that move through 360° should be driven with signals that are accurate to at least ± 1/2% or 1 part in 720. In fact if the overall system accuracy is to be maintained at ± 1/2°, then the drive signal should be considerably better than this and accuracies of 1 part in 1000 or 0.1% have been found to be desirable. Similarly the input signal resolution should be 1/5° (1 part in 1800) or better in order to avoid discernible stepping of the pointer. Signals to and from visual systems and signals that close autopilot loops are still more demanding of both accuracy and resolution and for this reason it is concluded that I/O equipment for the UPTRSS should be provided with converters with a minimum of 13 bit resolution and 10 bit (±0.1%) accuracy.

5.3.4 Computer Input/Output Channel Requirements

The computer input/output channel requirements are closely related to the data rates required by the I/O devices and depend in large

measure on the method of packing the inputs and outputs (see Figure 22). For example, if discrete inputs and outputs are transferred one bit at a time, a considerably higher data rate will be required than if they are packed into groups according to the word length of the computer.

For the purpose of this study, a worst-case estimate has been developed assuming that discrete inputs and outputs are transferred one bit at a time and that all inputs and outputs are updated at a 20-per-second rate. This estimate assumes an I/O channel with the characteristics previously defined as the most desirable (viz., a buffered, multiplexed block-transfer channel with memory overlap and a capability of servicing 16 or more devices). The rates given are word rates. If a byte-oriented channel is used, the word rates must be multiplied by the number of bytes per word.

TYPE	NO. OF CHANNELS	UPDATE RATE	DATA RATE
Discrete Outputs	4500	20/sec	90,000 words/sec
Discrete Inputs	6000	20/sec	120,000 words/sec
Analog Outputs	900	20/sec	18,000 words/sec
Analog Inputs	450	20/sec	9,000 words/sec
Total			237,000 words/sec

Figure 22 COMPUTER I/O CHANNEL DATA RATES

5.3.5 Construction

One further consideration is the construction of the computer interface equipment. Because of the large number of inputs and outputs required for the UPTRSS, it is imperative that adequate attention be given to the problem of achieving maximum reliability and maintainability.

Extensive use of integrated circuits, including some of the recently developed medium-scale integrated circuit (MSI) devices, is virtually a requirement for an interface system of the magnitude of that required for the UPTRSS. The use of integrated circuits contributes to reliability by reducing the parts count and the number of interconnections required in a system. The use of integrated circuits also results in reduced cost and contributes to maintainability by increasing the level of replaceability. That is, a smaller number of low-cost replaceable parts is incorporated in the system, thus reducing the diagnostic effort required of the maintenance technicians.

Another factor which contributes to maintainability is the provision of adequate test features. At the same time, such features should not require significant increases in system complexity because this would reduce the reliability of the system. In general, the hardware required to implement a test feature should not exceed 10% of the hardware which would not be tested if the test feature were omitted. This applies primarily to automatic test features since manual test features such as test points and indicators do not normally have a significant effect on system complexity.

6. MATHEMATICAL MODELS

Current state-of-the-art high-fidelity simulators use a modular math model approach for essentially the same reasons that complex electronic systems are composed of modular circuit boards: ease of design, speed and validity of checkout, and minimization of lost time in maintenance. Because simulators are composed of numerous subsystems that are, to various degrees, computationally independent of one another, they are ideally suited to a modular software approach. Each subsystem becomes an independent module within the total simulator software package. Simulator manufactures capitalize on the modular approach as an efficient way of coordinating design and minimizing checkout and troubleshooting time. There appears to be no reason to deviate from this approach in the consideration of the UPTRSS simulators. On the contrary, considering the intent of the UPTRSS, there is even greater reason to stress the importance of a modular software approach.

Since one of the primary endeavors of the UPTRSS is to be continued investigation into simulation software in an attempt to maximize training value while minimizing computational requirements, it is evident that the research investigators will be working with the software extensively. Just as the modular software approach aids the manufacturer during simulator checkout, this same approach will aid the investigator during research by causing the total software package to appear as the sum of individual parts which can be easily identified, isolated, analyzed, and, if desired, altered. These attributes are certainly desired in a research tool.

Of secondary importance is the ability to maximize the depth of understanding within the individual research investigator. Rather than forcing the investigator to attempt to understand the total simulator software package in great depth, modularizing permits the investigator to specialize and concentrate his efforts in particular areas. The persons responsible for the whole package need not concern themselves with subsystem equation optimization — these areas can be investigated in depth by associates — and may concentrate their efforts on subsystem interrelationships, with chief concern extending only to the interface level.

6.1 MATH MODEL ACCURACY

The depth to which a math model remains an accurate representation of the system or subsystem it is intended to simulate depends to a large extent upon the tolerance level to be met, the extent to which external control inputs must be supplied, and the desired spectrum of malfunctions within the systems.

For the UPTRSS requirements it is recommended that current state-of-the-art modular mathematical techniques be employed. This

recommendation is based upon the fact that current state-of-the-art techniques meeting the tolerance and malfunction requirements of MIL-T-9212B should and would adequately satisfy the tolerance level and malfunction spectrum for the UPTRSS simulators.

6.2 ITERATION RATES

As mentioned in Section 3 the iteration rates employed for each UPTRSS simulator should be variable within each software subsystem. The limits of iteration rate, however, should be constrained by the following basic considerations:

1) The highest iteration rate available for a given subsystem should be that rate defined as providing a high-fidelity solution.

2) The lowest rate available should be set as that lowest rate at which the subsystem remains dynamically stable.

A capability to command preset rates between the predetermined high and low values should be provided. In this manner, the investigator will be capable of evaluating the changes in training results with respect to the increase or decrease of computational load.

It is recommended that it be possible to change the iteration rate in any math model subsystem by using an input peripheral, such as a keyboard or multiposition switch, which enables these changes to be made without reloading the program.

6.3 MALFUNCTIONS

Current state-of-the-art malfunction capability is represented by MIL-T-9212B. Those malfunctions applicable to T-37 and T-38 are listed below. The implementation of malfunction selection equipment for the UPTRSS has been discussed in Section 4.

6.3.1 T-37 Simulators

The following malfunctions are recommended for the T-37 simulators:

1) Instruments (all flight, engine and system)

2) Engines:

   a) Total (i.e., turbine structural failures, etc.)

b) Thrust attenuators

c) Starting ignition

d) APU fail

e) Oil pressure

f) Fire

g) Overheat

h) Icing

i) Hung start

j) Hot start

3) Fuel System

a) Main fuel pump

b) Fuel boost pump

c) Fuel leak (fast and slow)

d) Valve

e) Filter

f) Icing

g) Fuel pressure (low to high)

h) Fuel flow (low to high)

i) Fuel controller

4) Electrical System

a) Battery

b) Generator (DC)

c) APU

d) Circuit breakers

e) Power switching systems

1) Changeover relays

2) Bus tie breakers

3) Bus limiters

f) Transformer rectifiers

g) Starter cutout

h) Overvoltage

i) Overload

j) Electrical fire

5) Hydraulic System:

a) Main pumps

b) Line

c) Brakes

d) Control surface actuators (frozen open and closed)

e) Selector valve

f) Accumulator

g) Condition indicators

6) Landing Gear and Doors:

a) Fail to extend and retract (individually)

b) Tires

c) Position indicators

d) Failure of lock (individually - up and down)

e) Brake

7) Flight Control Failures:

a) Trim control (fail, runaway)

b) Control disconnects

c) Control boost (normal to slow and fail)

d) Stability augmenters

8) Cabin Pressure and Air Conditioning:

a) Control components

b) Temperature

9) De-Ice and Anti-Icing System:

a) Detection elements

b) Control elements

c) Heating elements

10) Miscellaneous:

a) Canopy release (normal and emergency)

b) Flaps (structural)

c) Landing gear (structural)

d) Speed brakes

e) Ejection seat (normal and emergency)

f) Oxygen system

g) Communication systems

h) Navigation systems

i) Instrument landing system

j) Spoiler blowback

k) Pitot icing

l) Control surface icing

6.3.2 T-38 Simulators

The malfunctions recommended for the T-38 simulators are the same as those recommended for the T-37 simulators, with the following additions:

1) Engines:

   a) Compressor stall

   b) Compressor bleed valve stuck (open and closed)

   c) Afterburner

   d) Variable tailpipe nozzles

   (Exclude thrust attenuators)

2) Electrical System:

   a) Generator (AC)

   (Exclude generator (DC)

3) Cabin Pressure and Air Conditioning

   a) Pressure surges, low and high pressure

   b) Accidental decompression

4) Miscellaneous - Omit spoiler blowback

6.4 FIDELITY OF SIMULATION

A detailed discussion of the recommendation for UPTRSS capability to change the fidelity of simulation is given in Section 3.

6.5 OPTIMIZATION OF COMPUTER TIME AND STORAGE

Section 5 discusses in detail the computer recommendations for the UPTRSS.

6.6 AUTOMATED TRAINING REQUIREMENTS

Section 11 discusses in detail state-of-the-art advanced training techniques. No specific recommendation for any technique is given; however, as stated in Section 5, adequate provision for advanced training software has been allocated in the UPTRSS computer complex.

6.7 INTEGRATION TECHNIQUES AND ORDER OF COMPUTATION

The integration techniques presently employed in state-of-the-art simulation are mainly rectangular and second-order Adams methods. Both of these techniques are by their very nature straightforward and among the most basic forms of numerical integration. These techniques are employed effectively in current F-4 simulation programs, except for the simulation of very quickly changing characteristics, such as for radar systems, and thus these techniques would appear to be adequate for the T-37 and T-38 simulation task. Other numerical techniques can be implemented, and considerable research time could be devoted to the determination of the result of various integration methods. Generally, optimum operation of any integration routine depends upon iteration rate, which in turn has impact on the computer requirements. Sufficient spare computer capability will be available for research in this area.

7. SOFTWARE REQUIREMENTS

This section of the report discusses the software required to make the computer for the UPTRSS a flexible and useful tool. Software may be defined as all of the programs provided with the computer. For the purposes of this study these programs will be categorized as operational programs, utility programs, and diagnostic programs.

7.1 OPERATIONAL PROGRAMS

The operational programs for the UPTRSS will consist of all of the programs that are required to perform the task of training and experimentation. These programs will include the on-line executive program or programs, the real-time simulation models for all of the four trainers, the input and output programs required to operate displays and consoles, the automatic scoring and evaluation programs, and the data comparison and analysis programs required by the experimenters.

7.1.1 Programming Language

The programming language traditionally used for writing flight simulator programs has been an assembly language. Programs which are coded into assembly language are then translated by means of an assembly program into the machine language or object code. The assembly language for any particular computer is very similar to the computer machine language in that instructions and data relate one-to-one. Usually, an assembly language instruction must be written for every machine language instruction that results. Coding in assembly language, therefore, is a time-consuming undertaking and necessitates a thorough knowledge of the computer instruction repertoire.

Assembly languages continue to be used by most simulator manufacturers because the resultant object code is efficient when compared to that produced by high-level languages, and because the personnel employed by the manufacturer have the necessary familiarity with the computer. After a simulator has been delivered, the user agency will normally make comparatively few program changes and these modifications can conveniently be coded using assembly (or even machine) language.

An assembly language, at its simplest consists of a symbolic method of expressing the elements of a computer instruction, for decoding and assembly into the proper binary format for the computer system. Many of the features are determined by the system hardware and have a format imposed upon them by the hardware. However, it is possible to add features to an assembly language not directly related to system hardware to improve the ease of programming.

The following features should be required for an assembly language.

1) The assembly language should be sufficient to express any legitimate computer instruction, including all register and flag bits.

2) The assembler should contain a DATA directive which causes the specified locations, on loading, to be loaded with the specified values. Data types should include octal or hexidecimal for machine-level operations, integer for counters and indices, scaled fixed-point decimal numbers for problem variables, and character string for generating messages for printout.

3) The assembler, in conjunction with the loader, should provide the capability for programming in modules which may be maintained in object (assembled) form and combined at load time. This is to allow changes to parts of the computer program without affecting unchanged sections, to minimize assembly time.

The following additional capabilities are desirable, though not essential.

4) A macro capability is useful for generating often-repeated sections of code, which are too short to be implemented as a pure subroutine.

5) Floating point operations, either for hardware or software computations, and floating point data directives are useful. It is desirable to use floating point arithmetic for its programming convenience but the resulting program may be less efficient than corresponding, fixed point arithmetic. Careful evaluation should be made to determine the extent to which it should be used in the aircraft simulation programs. The floating point capability should be used wherever possible.

The UPTRSS, however, will be utilized in quite a different manner, and the very nature of the experimental tasks will imply a considerable amount of program modifications and additions on a continuing basis. For this reason, it is believed that the operational programs should be written in a high-level (compiler) language and the compiler and all documentation should be provided with the facility for use during updating and modification. Provision of a good compiler should relieve the operators of much of the tedium associated with coding and debugging in an assembly language.

Compiler languages are popular because they allow the programmer, in the average program, to ignore the complicated bookkeeping and transformation of the problem required by assembly languages. The compiler language will usually closely match the language in which the problem is stated and little need be known about the problem variables but their names. Once the mathematics of the problem are stated, little need be done to convert to a computer program using a compiler.

Yet, despite the many advantages of a compiler language, compilers have been slow in arriving in the simulator world. Let us examine the most commonly stated arguments against compilers:

1) Compiler object code is inefficient - This was a definite objection with many first- and second-generation computer systems. The state of the art in compiler design required straightforward coding of the source language without the code-economizing rearrangements of terms which even a novice programmer would spot. Code from these compilers was frequently twice as long as code generated in assembly language by experienced programmers. The conveniences of compiler-level programming were not adequate to cover a penalty of doubling the computers required. With third-generation computers, a new generation of compilers is also available. Now most compilers can make a careful scan of the input language and arrange an efficient order of computation. Indeed, many compiler developers can point with pride to some benchmark problem in which their compiler outperformed an assembly language programmer. So, although the efficiency problem can be overcome, it is still necessary to review each compiler proposed to assure that it is efficient for a simulator applications. This is especially true of engineering languages, for frequently the newly won efficiency has been traded for more extensive run-time diagnostic aids or more elaborate language features, such as re-entrant programming. Although diagnostics are helpful in checkout, they are not required by the time the program is ready for the simulator.

2) Compilers generate floating-point code - This was (and still is) true of Fortran and PL-1, and Algol, the most popular languages. And, on all computers studied to date, floating-point hardware is slower than fixed point. The major advantage of floating point is that coding is simplified. Although Fortran and PL-1 do have fixed-point variable modes and generate fixed-point code, the variables are restricted to integer values, which means they must all be scaled up and then the programmer must multitiply by powers of 2 to perform the necessary scaling. However, it is possible to specify a Fortran-like language to generate fixed-point code, so this problem can be overcome.

3) Compilers cannot handle large data pools - This problem is seldom stated, for few people have considered compilers for simulation after encountering the two objections above. Yet it is a major stumbling block. As discussed below, a simulator program is ideally composed of modules communicating through a data pool. This data pool will be large, on the order of 6,000 variables for a simple aircraft. By careful ordering of computations, the number of variables exchanged between modules can probably be reduced to 2,000. But these variables must be relatively fixed so that individual modules may be recompiled and integrated with previously compiled modules. In an assembly language program, this is done by writing code to define each variable. For Fortran, this would mean a COMMON statement three pages long at the head of each module, with all the attendant bookkeeping problems in keeping all the COMMON statements compatible. The only other alternative is to eliminate program modules and recompile the entire program.

A compiler language for simulation, then, should incorporate some sort of dictionary procedure for maintaining a data pool. This is especially true for a fixed-point compiler, for the compiler must know the scale factor of each variable to generate fixed-point code.

A properly designed compiler language and processor, then, is feasible for the UPTRSS as an alternate to assembly language programming. It is desirable to have it rely as much as possible on existing compilers since many programmers and engineers are already familiar with these languages. Additionally, it should have the features described above, namely:

1) Object code rendition of the source language should primarily be designed to be efficient, and other considerations should be secondary.

2) Fixed-point code should be generated, with proper scaling done by the compiler.

3) An efficient dictionary procedure should be provided for defining the data pool to the computer.

No compiler that is presently offered by digital computer equipment manufacturers possesses the characteristics necessary to produce efficient code for the simulation problem. It is therefore recommended that the aircraft simulation be programmed in assembler language. (A compiler developed expressly for the flight simulation problem could produce sufficiently efficient code and would have the attendant advantages of a higher-level language.)

7.1.2 Structure of the Executive Program

The conventional method of executive control for a real-time simulation program is to employ a simple scheduling executive. This control program is "called" at specific time intervals (e.g., every 50 milliseconds) by means of real-time clock interrupts. The task of the executive after each call is to schedule and call in the routines to be executed during the next time interval, or "frame". Typically the scheduling task is very simple because the iteration rates and therefore the scheduling sequences of the various routines have been specified by the programmer and remain fixed during simulator operation.

With a multi-processor configuration this scheduling executive becomes slightly more complex because the monitor now has the additional "first level" task of maintaining synchronization among the processors. However, if the individual framing rates remain fixed, then the executive task remains minimal. A typical executive program of this type would utilize 300 words of memory and 10 milliseconds per second of processing time per CPU.

It has been pointed out that the scheduling of program utilization on a fixed framing basis is very wasteful of machine time. Repetition rates for the various routines, which are established on the basis of providing good response during dynamic conditions, tend to be far greater than necessary during steady-state conditions. For example, a repetition rate of five solutions per second will provide adequate dynamic response for most engine equations, but during steady-state (e.g., cruise) conditions, updating the equations once every 2 or 3 seconds should be sufficient to account for the slowly varying ambient conditions.

One obvious method of providing more efficient scheduling would be to design an executive program that would schedule all routines on an interruptable basis, with rates dependent upon operating conditions. For example, the engine routines would be executed at a very slow rate until interrupted by a change in power setting, at which time the rate would be greatly increased. Although this type of executive would be much more sophisticated and would require more processor time, the overall increase in program efficiency could theoretically justify such increases.

Unfortunately, the nature of simulator operation is such that "worst case" dynamic conditions occur in most aircraft systems at the same time. During a final ILS approach, for example, flight controls are being exercised, hydraulic systems are changing, radios are being tuned, electrical systems are varying, etc. Under these conditions the use of a powerful executive program would only add to the worst-case computer loading. The overall effect would be to save computer time during cruise conditions (when

the additional time is not required) but to waste computer time during critical maneuvers. For this reason the use of a powerful executive that responds to programmed interrupts is not recommended for the scheduling of simulation routines for aircraft systems.

On the other hand, the use of interruptable routines to monitor instructor control panel operation is quite feasible. The standard simulator practice is to monitor all I/O at the rate of 10 or 20 iterations per second. Since some instructor panels are not operated for long intervals, such a practice is wasteful of processor time. The degree of inefficiency is not significant for small simulators; however, the UPTRSS will contain a large number of instructor and experimenter consoles and therefore it would appear desirable to interrogate these consoles on an as-required basis.

It is therefore recommended that the executive program be structured so as to provide for interruptable scanning of selected panels and consoles. The scheduling of operational system programs may, however, be accomplished on a simple "training" base with the provision that individual iteration rates be easily modified to enable experimental variation of simulation fidelity.

7.1.3 Sharing of Simulation Routines

Because the recommended UPTRSS contains duplicate cockpits (two T-37's and two T-38's), a scheme whereby a single program would be utilized for two cockpits would appear to merit consideration. For example, a single set of flight equations could be treated as a subroutine for both T-37 trainers and could be entered once for the computations associated with one cockpit and then a second time for the computations associated with the second cockpit. In fact, since certain programs are common to all simulators, some of the equations of motion could conceivably be treated as subroutines for all four trainers. The advantages of such technique would be that computer memory would be minimized and, theoretically at least, programming time saved because such equations would have to be coded and debugged only once.

However, there are a good many practical reasons for not recommending program sharing among simulators, and some of the more important of these are:

1) The initial programming effort involved in subroutining instructions is quite extensive. All instructions that make reference to variables and parameters peculiar to one trainer will have to be written as indexed or indirectly addressed instructions. The administrative overhead associated with documenting such routines quickly becomes excessive if many programs are involved.

2) Subroutined programs might make the individual testing of trainers more difficult. Program integration and hardware checkout would likely occur on an individual basis for each trainer and yet common programs which had been checked for one cockpit might be unuseable (due to indexing errors, etc.) when applied to a second cockpit. Under these conditions errors could be difficult to find and simulator checkout time could become excessive.

3) The use of subroutined programs would make changes more difficult to implement for the reasons discussed in 1) above.

4) Because of the UPTRSS' requirement to investigate fidelity of simulation, it would appear highly advantageous to provide the capability of modifying the programs in one trainer while leaving unchanged the equivalent programs in the duplicate machine. Such provision would enable the effects of changes in iteration rates, program degradation, etc., to be directly evaluated and compared. The use of common subroutines would not permit this type of comparison.

Because of these consideration, primarily number 4), the programming of shared routines among the UPTRSS trainers is not recommended.

7.2 UTILITY PROGRAMS

Utility programs are those routines used for loading, dumping, formatting, converting, and general data handling. Some of the utility programs for the UPTRSS will run on-line during simulation exercises, while other routines will be available for off-line utilization. A good set of utility programs is required with any computer installation to facilitate communication with the machine, and this requirement will be particularly important for the UPTRSS complex.

The structure of the executive or monitor program for real-time simulation was discussed in 7.1.2. In addition to the capability of managing all operational simulation processes, this executive must also be capable of servicing requests for utility programs. It is considered essential, for convenience of computer utilization, that utility programs be available on call (e.g., through the TTY) to the operator. This means that the executive program must be designed to interpret coded inputs typed on the TTY and to respond by halting the simulation program and calling in the appropriate utility program.

The following utility programs are recommended for the UPTRSS computer complex:

1) A algebraic-type compiler capable of running on the delivered complex and of producing object code in relocatable format.

2) An assembler program that will accept inputs coded in the mnemonic or symbolic language of the particular computer and will output object code in relocatable format. The assembler must be capable of assembling individual program modules so that when changes are made, only the affected module need be reassembled. The assembler should also be capable of generating a magnetic tape, in standard IBM tape format, suitable for outputting through a line printer in the form of a hard-copy program listing. The listing should present in parallel columns the following items: relative location, machine language instruction, symbolic language instruction, programmer notations, and assembly-program-generated comments. The availability of an assembler will enable the computer user to make changes in symbolic language for routines where the use of the compiler may not be convenient or desirable.

3) A relocatable program loader that will accept the relocatable object tapes generated by the compiler or assembler and produce an absolute object program in core memory for execution by the computer. The relocatable loader must also be capable of checking to ensure that the program has been properly loaded (via check sums, parity checks, etc.).

4) An absolute binary loader which will be capable of reloading the computer with a previously loaded program which has been dumped on magnetic tape. This loader will, of course, be much faster than the relocatable loader and will enable the entire computer to be reloaded in a few seconds.

5) An in-line debugging program which can be made accessible during simulation processing and used to dynamically change core, to produce snap-shot dumps of core, to input data to some intermediate storage device in a fully acceptable data format, and for other things. This program could be used to run in simulated real tir allowing on-the-spot examination of time-dependent parameters.

6) An off-line trace routine whose output could be retrieved on a number of peripheral devices, thus permitting immediate or deferred hard-copy examination of results.

7) A post-mortem dump and analysis routine that will return, on hard-copy output, a properly formatted "dump" of core, compressed if necessary, so as to preclude printing of consecutive locations containing identical information (e.g., several thousand core locations set to zero). This routine would also provide information such as computer status words, time elapsed from some reference time to the beginning of execution of the dump routine, and various other supplemental features.

8) I/O handling routines general in their makeup to eliminate redundant programming by any other simulation programs.

9) A general I/O and edit program that can be used to copy tapes, list files from various peripheral devices, update source coding contained on some storage medium, allow for conversion formatting (octal input retrieved in alphanumeric format), and various other auxiliary tasks.

10) Other programs more or less dependent upon the computer complex utilized might include a digital plot routine, instrumentation-oriented programs such as graphic displays, audio/visual response programs, and hardware interface programs.

7.3 DIAGNOSTIC PROGRAMS

Diagnostic programs are those routines which assist the computer operator in checking the status of the computer and interface hardware and in isolating failure conditions.

The following diagnostic programs are recommended for the UPTRSS computer complex:

1) An on-line loop check of the interface or linkage system to determine that the computer I/O channels and the real-time interface converters are functioning properly. Implementation of this diagnostic will necessitate an interface hardware design that closes the loop by tying interface outputs to interface inputs. Many possibilities exist for providing such interconnection, including mechanical patch boards, complex switching matrices, and complete duplication of all channels for test purposes. For the on-line loop check it is recommended that two test loops be provided for each cockpit. One loop will consist of an analog output connected to an analog input, while the other will consist of a discrete (switch) output connected to a discrete input. This approach requires a minimum of redundant hardware, while enabling the diagnostic to check the computer I/O processor and all interface controllers. Checking of each interface channel will be accomplished by the off-line interface diagnostic.

2) A morning readiness check which would provide the operator with a quick "go/no-go" simulator status check. It is recommended that this check be performed with an operator in the cockpit and that the program can be designed to check hardware rather than verify the operational program. As part of the check the computer could output to each instrument or display a series of static and dynamic outputs which would permit visual verification of the operation of each instrument or display.

3) A program test and verification diagnostic which would enable the operator to verify the performance of the operational program. This feature could be implemented by recording on magnetic tape the program outputs and inputs that occur during an exercise. This master tape would then be used during the diagnostic test to drive the operational program with the

recorded inputs and the newly computed outputs would be compared with the previous values stored on magnetic tape. Errors and discrepancies would be printed out on the computer line printer for analysis by the operator. It is envisioned that this program would be utilized to check the correct functioning of the operational program after each complete load.

4) An off-line interface or linkage test program designed to selectively test all interface channels. It is recommended that this test be an automatic loop test that is not dependent upon operator observance of instrument response. The implementation of such a feature will require the linkage hardware to be so designed as to selectively tie outputs to inputs for both analog and discrete quantities. A large variety of hardware designs are possible; however, it is recommended that the implementation be such that the hardware required is no more than 10% of the channel hardware to be tested. The diagnostic should also permit the user to request (via the teletypewriter) that a specific channel be tested continually so that intermittent faults can be located.

5) CPU and memory "area level" diagnostics that will facilitate the location and correction of malfunctions. These diagnostics are normally supplied by the digital computer manufacturer as part of a standard software package.

6) Peripheral equipment diagnostics that will test the operation of each computer peripheral and will signal the operator, by means of typewriter output, of errors that are detected.

7.4 PROGRAM MODIFICATION AIDS

The compiler and assembler programs that have previously been discussed will provide the necessary means of modifying the operational programs for the UPTRSS simulators. However, there are two types of program data peculiar to flight simulators that will require special programs to facilitate modification. The two types of data are function data and radio aids data. There are many techniques that can be considered in these two areas. The method utilized for the UPTRSS must lend itself to ease of change of data. Special programs must be prepared to enable the user to make changes readily. The following paragraphs include a description of one acceptable technique for function data and one for radio aids data and the programming aids required for each.

Function data consists of the stored breakpoint values for all nonlinear functions of independent variables. This function data is continually accessed by the linear interpolation routine during program execution. Radio aids data consists of the stored parameters for all radio facilities. This data is accessed by the facility selector routine during program execution.

It is, of course, essential that the simulator user be provided with a convenient means of updating these data blocks, since both function data and radio facility data are subject to change. The recommended means of accomplishing the required updating is to employ special data packing and formatting programs commonly called "function data compilers" and "radio data compilers."

7.4.1 Function Data Compiler

This compiler should be capable of accepting data in the form of decimal numbers input on punched cards and formatting this data into a condensed block of binary numbers for storage in the digital computer. The storage format will depend upon the linear interpolator call routine, but in general the numerical or breakpoint values of functions of any one variable will be stored consecutively in core. In order to save core memory, it is recommended that the compiler be designed to pack all function data into consecutive locations within memory so that no spare memory exists between functions. Expansion will then be accomplished by recompiling the function data area. In order to facilitate such recompilation, it is recommended that the function data compiler be provided with an edit capability. Such a feature would enable a single block of data to be individually compiled and then edited into the function data block.

7.4.2 Radio Aids Data Compiler

This compiler shall be capable of accepting radio facility data in convenient punched-card notation formatting this data into a condensed block of storage.

The compiler should be capable of compiling by small blocks or modules, and an edit capability should be provided that will permit individual radio facilit es to be modified by the user.

8. MOTION SIMULATION

8.1 STUDY APPROACH

Motion cue simulation requirements were investigated for the following training maneuvers:

1) Airwork and aerobatics

2) Circling approach

3) Takeoff and landing

4) Formation

5) Navigation

6) Low-level flight

7) Night flight

8) Instrument flying

Much of the investigation was subjective in nature, and the substance of the findings is briefly reported in Section 8.2. It was concluded that a six-degree-of-freedom motion system, with an auxiliary device for the simulation of sustained acceleration, is required for the Undergraduate Pilot Training Research Simulation System. Only if this approach is adopted will the full potential training value of the various drive signal formulation programs be realized in simulating the required maneuvers in six or fewer degrees of freedom, while maintaining sufficient flexibility for changing the "fidelity" of simulation. Consideration of the importance of each degree of freedom relative to each maneuver leads to a variety of compromise systems; however, any compromise tends to defeat the objective of the UPTRSS.

Subjective considerations, although of considerable value, are not really a sufficient basis for arriving at the conclusion stated above. Section 8.2.2 reviews, on a more quantitative basis, the rotational and translational requirements for motion simulation and formulates a rationale for the determination of excursion requirements in six degrees of freedom. Considerable use is made of an example in which this rationale has been applied.

A considerable number of factors affect the dynamic capability of a motion system. Section 8.2.3 discusses the desirable characteristics of servo actuator dynamics. Emphasis is placed upon hydraulic devices because of their superior performance.

Section 8.2.4 considers in detail the desirable and essential operational features that should be a part of a system design. The section also reviews electrical control, mechanical and hydraulic design considerations, and safety.

The performance of a motion system is dependent upon the drive signal formulation. Section 8.3 discusses typical and state-of-the-art approaches to driving motion systems from digital computers. The section concludes that an essential part of the UPTRSS should be the evaluation and comparison of various drive signal formulations, utilizing the entire range of degrees of freedom.

Section 8.4 discusses various techniques for implementing devices capable of providing sustained acceleration or deceleration simulation. Verification of the requirements for such devices has been sadly lacking, and it is felt that one objective of the facility should be to evaluate their utility.

Section 8.5 summarizes the conclusions of the study, and specifies the T-37 and T-38 motion simulation requirements. Four systems are specified, one corresponding to each visual system recommendation (see Section 9.3).

8.2 SCOPE OF STUDY

8.2.1 Subjective Assessment of Maneuvers

A discussion of the motion simulation requirements can be approached from a subjective evaluation of the curricula and the maneuvers performed by the undergraduate students in the current training program. A discussion of this form is included and is significant, in that it reflects some of the opinions of experienced aviation psychologists and pilots directly involved in the study. No research to date has completely or even partially specified these requirements; indeed, the definition and utilization of UPTRSS is a means towards this end.

The contents of Section 8.2.1 should be taken as indicative of the subjective discussions that were conducted during the many hours devoted to this phase of the study, but by no means as a complete summary of the minutes of such meetings.

8.2.1.1 Aerobatics and Airwork

An important simulation requirement for the majority of maneuvers in aerobatics and airwork would appear to be that of reproducing the effects of sustained accelerative and decelerative forces on the pilot. Sustained force sensations, together with external visual references, are cues sensed by the pilot in normal airwork and during aerobatic maneuvers,

and would seem to contribute significantly during flight. For example, in maneuvers such as the loop, the sense of increased force is used as a guide to controlling the airplane during the maneuver. This maneuver is performed at high altitude where the visual sensation of translational motion is relatively insignificant compared with the significance of the rotational aspect changes. Practically all of the aerobatic maneuvers use the horizon and some other fixed reference on the airplane to guide the pilot — e.g., leveling off, level turns, chandelle, lazy 8, power-on stall, etc. — and in each case the primary motion observed is that of rotation. The translational capability is important, however, particularly in providing those subtle acceleration "onset cues" which are present during any change of acceleration and which provide a more complete and realistic environment for the pilot. It is thought by some leading authorities in the simulation field that the presence of these acceleration onset cues in a motion simulator prevents nausea due to the dichotomy of information being presented to the brain from visual and motion environments in a simulator. No experimental support for this hypothesis can be found, although many reports exist of nausea experienced during simulator operation utilizing visual simulation equipment.*

Uncoordinated roll maneuvers may occur during training, and the effects may be readily observed on instruments, but since the majority of all maneuvers are coordinated, unless particular importance is attached to training for uncoordinated maneuvers the roll rotational angular requirement would appear to be of low priority. However, from another viewpoint the roll angular acceleration "onset cue" may be of significance in initiating roll maneuvers around, or close to, the longitudinal aircraft axis (for roll acceleration greater than about 3 deg/sec^2 — see Phase I report). For pitch rotation, the onset of pitch rotation, in the T-37, for example, may be felt primarily as a rotational motion, since the pilot is close to the aircraft center of gravity. In the T-38 the requirement is different; since the pilot is well forward of the aircraft center of gravity, pitching will be observed as an attitude change but sensed primarily as a vertical motion. Undoubtedly the aircraft is exercised in all six degrees of freedom, with both sustained force and the first derivative of force being of importance.

8.2.1.2 Mach and Stall Buffet

As stall speed is approached, buffeting occurs, which is in general multidirectional and of variable amplitude and frequency. This buffeting is an important motion cue, signaling that a stall and spin condition is being approached along the current flight path. Accurate representation of the multidirectional perturbations would require a simulator with high-

* ASD TR 61-530 Aeronautical Systems Division, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio. "MOTION SICKNESS AND SPATIAL PERCEPTION - A Theoretical Study", Jack E. Steele, Major, USAF (MC). November 1961.

frequency and variable amplitude response capability - i.e., a motion system capable of responding to frequencies of approximately 5-10 cycles per second in six degrees of freedom. Flights in the T-38 may also approach Mach 1 and encounter Mach buffet. A buffet capability has frequently been provided in simple simulator systems for the pitch degree of freedom only, since pitch is in general the flight parameter which is most affected (e.g., the F-4E), and it is questionable that replacing the true buffet sensation with buffet only in the pitch degree of freedom would result in any considerable reduction in training value. This clearly is an area for research in the undergraduate program to result in the optimum definition of requirements for this phase of flight.

8.2.1.3 Circling Approach and Landing

In this flight regime the longitudinal forces would not seem predominant, since at the start of the maneuver reduced speeds have already been attained. Decrease in altitude, especially on the final turn, is significant, and the requirement for vertical acceleration simulation and pitch capability is evident. For the coordinated turn, the roll degree of freedom is not required, since the acceleration vector will force the pilot directly into his seat, and thus roll can then be simulated by visual reference alone. However, as stated before, the roll rotational acceleration and onset cue may be an important cue.

Crosswind landing is an important part of the training curriculum. The forces generated by the crosswind result in yaw and lateral accelerations by the aircraft which must be corrected by the pilot. To provide the yaw and lateral motion capability in a simulator would seem desirable. Rotation is perhaps less important in the T-37 and can possibly be simulated by the visual system alone, since the distance between the pilot's head and the center of gravity of the aircraft along the longitudinal axis is small. In a T-38 lateral onset may be an important cue. Clearly, the complexity of flying this maneuver, together with effects such as ground effects, cross winds, landing impact, longitudinal forces, etc., requires six-degree-of-freedom simulation capabilities, with a recommendation for an additional sustained force capability for deceleration after landing.

8.2.1.4 Takeoff, Taxi

The primary requirement for simulating the taxiing task is a visual simulation system. The motion simulation requirements are less critical. Small-amplitude oscillations of low frequency, random and multidirectional, characterize the surface qualities of the runway; similar characteristics are apparent during takeoff and landing on unimproved surfaces. The distinction between taxiing and airborne conditions is evidenced by the decrease in the effect of these vibrations, and the sensation produced when the wings provide enough lift to lighten the load on the gear. The primary motion cues in the takeoff phase of flight are the prolonged longitudinal

acceleration that occurs, the change in pitch attitude at rotation and during climbing, and the heave motion associated with climbing. The combination of these effects is extremely important in the accurate simulation of this phase of flight.

Effects such as retraction of the landing gear would appear to be of secondary importance; adequate simulation could be obtained from aural effects. "Takeoff, engine out" in T-37/38 aircraft does not produce any noticeable lateral effects.

8.2.1.5 Low-Level Flight

Severe turbulence disturbances can occur during low-level flight maneuvers, and it would appear of necessity to provide capability in all six degrees of freedom to provide for realistic simulation. As stated in Section 8.2.1.2, a simpler and compromise motion simulation would be to provide buffet in the pitch degree of freedom only. Again several compromise motion systems could be discussed, ranging from six to a single degree of freedom, each of these resulting in steadily degraded capability and steadily reduced cost. However, the extent of the degradation in training value as the number of degrees of freedom is reduced is still a matter to be determined.

8.2.1.6 Formation Flight

Here the primary cues are obtained from the visual scene. The subtle changes in thrust required to remain in close formation are important cues, however, and the pilot learns to make these changes from the thrust response characteristics of the airplane without severe overcompensation. The effects of changes in thrust setting are gradual, and it would be desirable to evaluate the use of devices that provide sustained and slowly changing forces encountered. Downwash effects may be felt when crossing behind the exhaust of the airplane ahead. The dynamics associated with this condition are discussed in Section 3.3.3. The forces generated act as a disturbing factor, tending to decrease the stability of flight and are thus an important part of the training environment.

8.2.1.7 Summary

Consideration in a similar manner of all the maneuvers listed in Section 8.1 leads to a requirement for simulation in six degrees of freedom for all eight categories, together with a recommendation for a sustained acceleration device for all maneuvers. This conclusion is based only on subjective discussion. The following section more closely examines the requirements, with a view to a more quantitative definition.

8.2.2 Simulator Motion Requirements

8.2.2.1 Introduction

No subjective discussion without experimental backup can be conclusive in the definition of simulator motion system requirements. It is not possible to show conclusively that motion simulation in six degrees of freedom is necessary, or that motion simulation in five degrees of freedom is significantly inferior to that in six. Certainly recent simulator procurements by military aviation, commercial aviation, and NASA have reflected a desire for six-degree-of-freedom simulators. The UPTRSS should provide an opportunity to determine the true motion simulator requirements for all flight phases, and perhaps for this reason alone the facility should be equipped with at least one six-degree-of-freedom system, with a sustained acceleration simulation device, the so-called "G-seat" (see Section 8.4). An attempt will be made here to assess more quantitatively the requirements for a motion system based on knowledge of dynamics, human factors considerations, and the physical limitations of state-of-the-art hardware.

8.2.2.2 Rotational Requirements

It is usual, when considering rotational motion, to reference such motions to the aircraft center of gravity, about the Euler axes. Rotational motion about these axes is transformed into both translational and rotational motion at the pilot's head, the magnitude of translational component increasing as the distance between the pilot's head and origin of coordinates at the center of gravity (in the directions of the orthogonal axes) increases. Clearly, in the T-38 the lateral translational motion due to yaw about the center of gravity is considerably more pronounced than that in the T-37, since in the T-38 the pilot is 13.7 feet forward of the center of gravity, as opposed to 2.1 feet in the T-37.

In both the T-37 and T-38 aircraft, pitch acceleration about the center of gravity produces (at the pilot's head) pitch acceleration, vertical acceleration, and the effects of continuous change in the apparent direction of the gravity vector, together with the normal component (longitudinal) of acceleration due to rotation. Roll acceleration about the center of gravity produces roll acceleration, lateral acceleration (because the pilot's head is above the longitudinal axis of these aircraft), the normal component of acceleration in the vertical plane, and a continuous change in the direction of the apparent gravity vector.

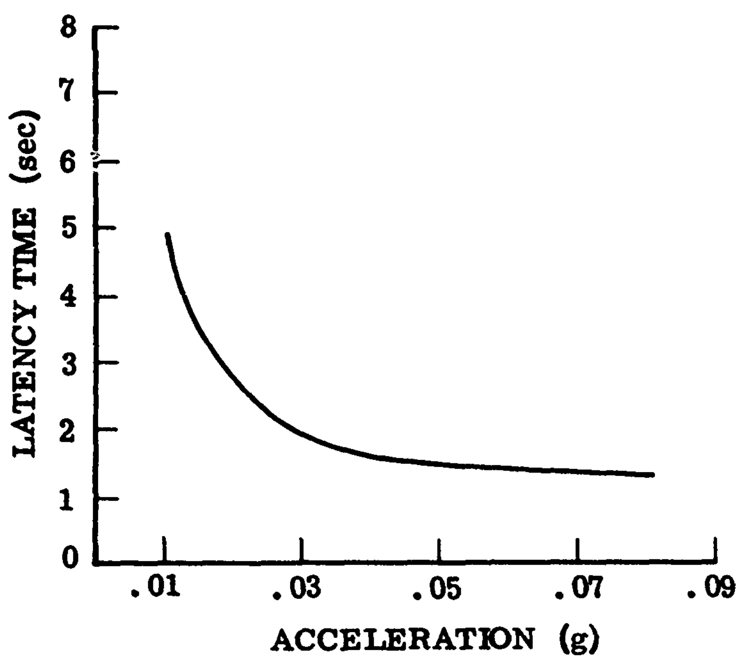
In many maneuvers performed in the T-37 and T-38, roll motion may be sensed initially by the onset of rotational acceleration. (As the position of the head becomes higher relative to the Euler axis, the rotational acceleration becomes primarily translational.) In coordinated roll

maneuvers the total sensed acceleration is directly along a vertical down through the pilot's body, and thus he may feel little more than a change in an apparent vertical acceleration. The visual references, however, will affirm his attitude. During an uncoordinated maneuver, side forces on the pilot are generated. It is important that these side forces not be generated as a result of excessive roll angle when a rotational acceleration cue is imparted.

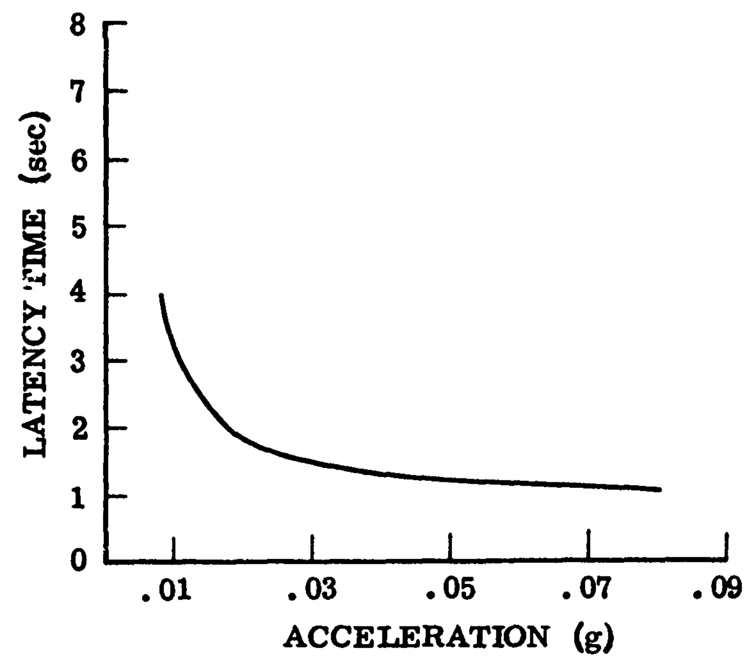
Rotational accelerations, sensed chiefly with the inner ear, are probably less important in aviation than linear accelerations. It should be noted that angular accelerations in pitch and roll (but not in yaw) rather quickly integrate into a perceptible change in the direction of the acceleration vector, and thus angular acceleration becomes compounded with angular position. As indicated in the Phase I report, a spectrum of acceleration sensitivity thresholds exists for both angular and linear degrees of freedom.* These values have been obtained primarily in idealized circumstances. For example, a recent study on human sensitivity to longitudinal acceleration, performed by Meiry** at M.I.T., using a darkened enclosure mounted on horizontal linear rail tracks, produced the acceleration/latency curve shown in Figure 23. This data shows that the absolute threshold of sensitivity in the upright position is 0.01g. Although of interest, this does not provide a great deal of insight into the simulator requirements, because like many experiments of this kind, task loading in, or analogous to, the simulator environment has not been considered. The qualitative effect of task loading is known to be decreased sensitivity to acceleration as the task complexity increases, and thus in simulator design nominal values for thresholds are selected. Thresholds for the perception of acceleration are approximately 0.02g to 0.08g for linear acceleration and approximately 3 degrees per second per second for angular acceleration of the head. The implication of these values on system design is discussed in Section 8.2.2.4. The problem is further compounded by human sensitivity to higher derivatives of acceleration – i.e., rate of change of acceleration, etc. As stated in the Phase I report, no definitive data with respect to the total simulator environment on the sensitivity to rate of change of acceleration may be found in the literature.

* Wendt, H.W. Link Engineering Report No. 763, Operator threshold values relevant for the design of moving base simulators.

** Meiry, J.L. The Vestibular System and Human Dynamic Space Orientation, NASA CR.628, Oct. 1966.



(a) Latency Times for Perception of Horizontal Linear Acceleration, Supine



(b) Latency Times for Perception of Horizontal Linear Acceleration, Upright

Figure 23 LATENCY TIMES FOR PERCEPTION OF HORIZONTAL LINEAR ACCELERATION

As is the case for aircraft performance characteristics studies in the past, accelerations in both the T-37 and T-38 will almost certainly exceed these perception thresholds considerably in each of the three linear and three angular degrees of freedom, and again there is justification for at least one of the simulators to have a six-degree-of-freedom capability.

Clearly, in defining the rotational or translational requirements of a research simulator severe compromises must be made. Due to the large weight of a T-37/T-38 with a visual system, and due to the nature of the components of visual systems, it is totally impracticable, if not technically beyond the state of the art, to provide 360° capability in each degree of freedom. Even if it were possible to accomplish this, the correct sensation in many maneuvers can result from a motion cue sensation coupled with an attitude change shown by the visual system,which may not require the full capabilities in all rotational degrees of freedom. Without a very careful study of the performance envelopes of the T-37 and T-38 aircraft for each of the critical maneuvers to determine the extent of motion environment requirements and the interaction between the motion and visual environmental requirements, it is not possible to absolutely define rotational requirements. One conclusion of this study must be that each maneuver should be examined to determine the requirements. To accomplish this an aircraft must be instrumented to measure attitude, accelerations, and higher derivatives of acceleration, and flown through the spectrum of training maneuvers. However it is possible to arrive at reasonable conclusions based upon experience in defining requirements for commercial simulation six-degree-of-freedom equipment. Guidelines for commercial aircraft are considerable easier to determine since the range of extremes of attitudes and maneuvers is considerably smaller than that of military trainers.

8.2.2.3 Translational Requirements

Clearly, in any ground-based simulator, since translational acceleration (due to translation or rotation), velocity, and displacement capabilities are very limited, it is impossible to reproduce the translational motion capability of the aircraft. However, as indicated in the Phase I report, the simulation of the onset region of an acceleration time history imparts particularly valuable training information. Simulation of the onset region of an aircraft acceleration has been used successfully for a number of years for a range of military and commercial simulators (see Section 8.3). However, recent advances in the state of the art of simulation with six-degree-of-freedom motion systems have led to the development of rationales for estimating translational excursion requirements. The problem of estimation, however, is compounded by the fact that any acceleration applied must be applied at some rate, and, as stated previously, this rate of change of acceleration, called jerk (or jolt), to which the body is sensitive but for which no exact published threshold data exist, has an effect that is inextricably confounded with the effect of acceleration itself.

Section 8.2.2.4 discusses an approach to estimating the requirements for translation, which is a logical extension of the discussion of the previous paragraph, and thus relies on examination of aircraft maneuvers. This technique has been successfully used by Link Division of Singer in the definition of commercial airline requirements, the rotational and translational capabilities being indicative of worst-case conditions.

The approach is presented here, and considers first a hypothetical electrohydraulic motion system moving in one degree of freedom. (See Section 8.2.3 for a discussion of the attributes of electromechanical, electro-hydraulic, and other prime movers.)

8.2.2.4 Translational Excursion Requirements in a Single Degree of Freedom

This section reviews the results of the studies conducted to determine the requirements for motion simulation as they relate to practical hardware limitations, and discusses the definition of the requirements necessary to provide training in an efficient manner.

With any ground-based simulator, the motion excursions are limited, compared with actual aircraft excursions. A wide variety of motion systems could be employed to perform simulator motion. The most desirable types are driven by hydraulic servo mechanisms (see Section 8.2.3), which exhibit smooth and quiet operation with high frequency responses and high reliability. However, actuation devices are subject to certain limitations in stroke length, velocity, and force (acceleration) capabilities. Stroke limitations are due to the mechanical limits of the actuators. Velocity limitations are due to hydraulic flow restrictions caused by flow availability from the pump source or by valve flow saturation. For a given flow Q and a given actuator cross-sectional area A, the velocity capability V is given by:

$$V = \frac{Q}{A}$$

The value Q is limited by economic considerations (e.g., pump costs, motor costs, etc). The acceleration limitations are due to the selected system pressures and hydraulic working areas within the actuators.

Consider the simulation of the translational motion of an aircraft, with respect to the acceleration time history of that motion in a translational direction. A typical aircraft acceleration profile is shown in Figure 24. The region ABC is the onset region. It is possible to reproduce the onset region of the acceleration, until the instant in time when the actuator reaches its maximum velocity. At this instant in time, the actuators can impart no further acceleration to the motion platform, and the platform will continue to

move with a constant velocity. Since the aircraft acceleration has been followed to the limit of hydraulic system capacity, the greatest possible motion sensation has been obtained from the simulator. This is because continued motion with constant velocity does not create any proprioceptive sensation. Figure 24b shows the acceleration time profiles of both aircraft and simulator up to the instant of attaining velocity limit.

The acceleration time profile of the simulator, ABCD, called the onset cue, is a measure of the training value that may be extracted from the simulator motion. Figure 25c illustrates an idealized onset cue, ACD, which will be used as a simple approximation to the curve ABCD for the purpose of the following example.

Consider a typical onset rate of change of acceleration of 5 g/second (this value is representative of a maneuver in a large transport aircraft, and has been recorded on a computer during a simulator exercise). Figure 25 compares the acceleration, velocity, and displacement characteristics of simulator and aircraft for the maneuver with a velocity limit of 2 feet/second. (A typical value on an existing three-degree-of-freedom system is 18 inches/second in heave).

It is clear that to reach a velocity limit of 2 feet/second:

1) The onset acceleration lasts for a period of 0.158 seconds, and this represents the period of positive training value.

2) An acceleration of 0.8 g is attained.

3) The distance traveled is 0.12 feet.

It is also clear that regardless of the mechanical design of the system, only 0.12 feet is required to impart maximum positive training in this case. Further, the training occurs during a very short period of time, and the nature of the cue is an impulse, or jerk, and will be felt as a jerk. The region CD of Figures 24a and 24b represents the removal of the force which imparted the original acceleration, but not a force in opposite direction. This sudden removal will occur in any system that is driven to velocity limit.

This sudden removal may be avoided by driving the system to a velocity considerably smaller than velocity limit, and removing the force along a profile BD as shown in Figure 26. This results in a differently shaped cue, which reaches a considerably lower acceleration level than in the previous case. However, this does not provide grounds to conclude that the training associated with one or the other type of cue is superior. As Wendt points out, for cues produced in short time periods (less than 1 second) the shape of the cue is relatively unimportant, and the impulsive energy content is the only significant factor. In fact, since the servo actuators are ideal, the

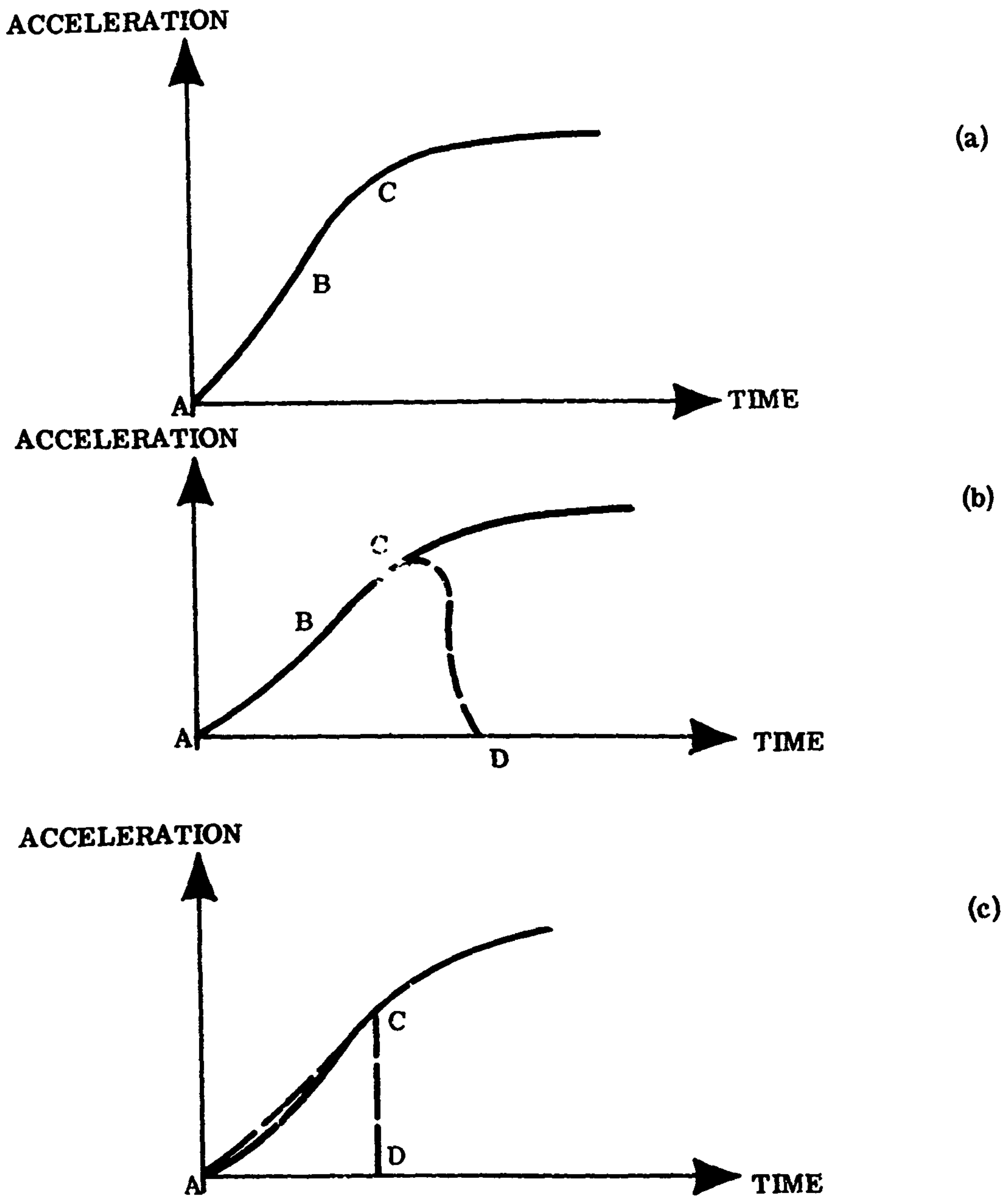


Figure 24 IDEAL ONSET CUE PROFILES

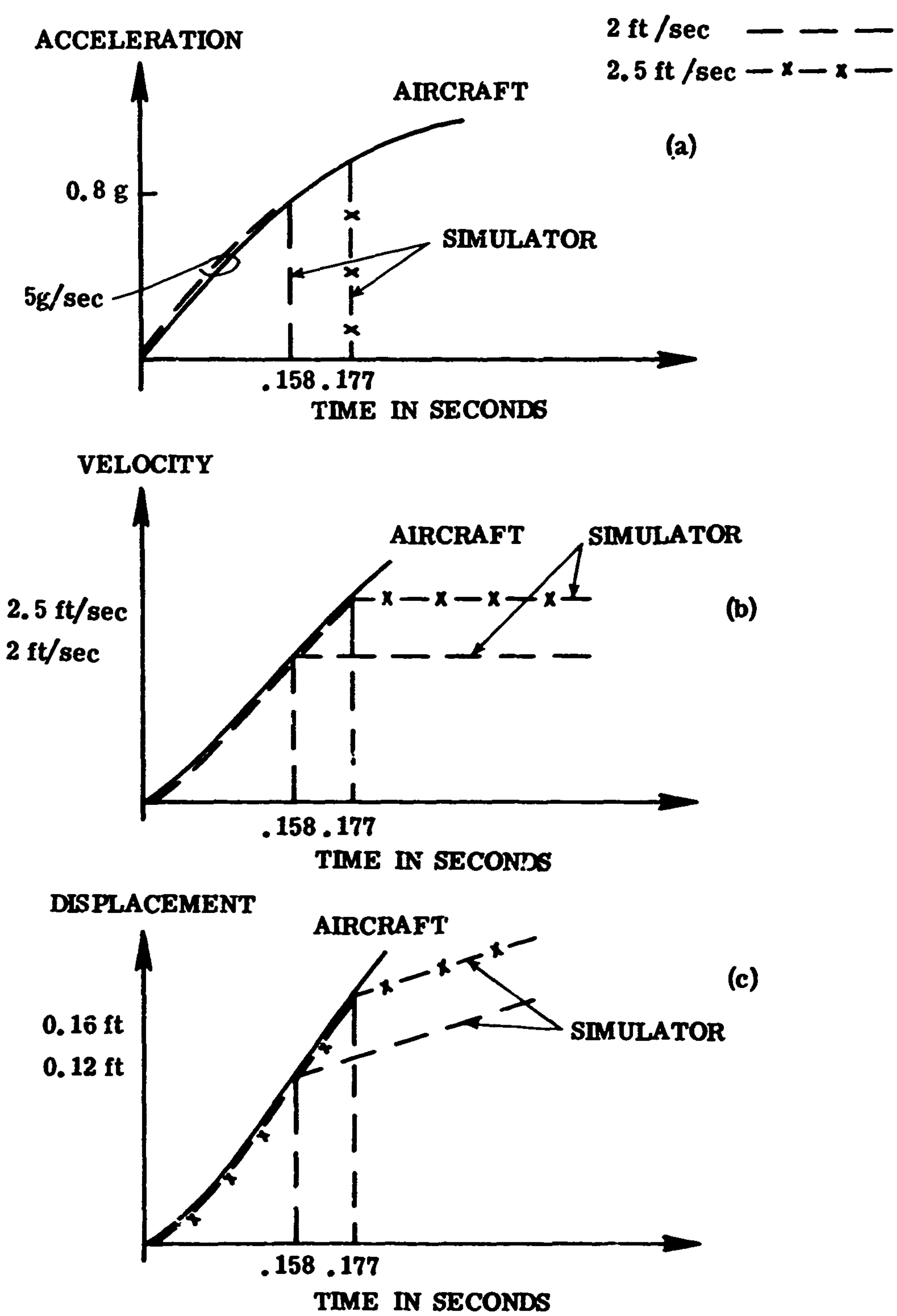


Figure 25 ACCELERATION, VELOCITY, AND DISPLACEMENT PROFILES FOR IDEAL CUES

instantaneous removal of a force (Figure 24c) becomes the shape illustrated in Figure 24b.

Continuing the example, the question arises, "What if one increases the velocity limit of the system — surely greater training value can be extracted from the simulator?" The answer to the question is yes. However, Figure 25 also shows the simulator performance with velocity limits of 2 ft/second and 2.5 ft/second, and the table below compares the values.

VELOCITY	TIME OF CUE	DISTANCE TRAVELED
2 ft/sec.	0.158 sec.	0.12 ft
2.5 ft/sec.	0.177 sec.	0.16 ft

It is clear that for 2.5 ft/sec., the "training value," equivalent to the time of the cue, increases very marginally (by only 0.021 seconds), and the distance required is still very small (.16 ft.). Figure 27 illustrates this effect more generally for a wide range of velocity limits and onset rates. Higher velocity limits provide no significant increase in cue duration, and in any case only a few inches of displacement are required. Note also that maneuvers which produce a higher rate of onset require smaller excursions before reaching velocity limit.

Consider Figure 24c again. At instant D, along the time scale axis, maximum velocity has been obtained, and since no motion sensation is associated with constant velocity, velocity washout should commence immediately for efficient operation. This ensures the maximum conservation of excursion and the minimization of system kinetic energy. By reducing the velocity, successive cues in the same sense as the first cue may be given, until maximum velocity is again reached.

It is important during the velocity-washout phase of motion that deceleration take place at a subliminal level to ensure that no "false" motion sensation cue is generated during this process. Human-factors researchers indicate that "acceptable" values, in situations where "attention" is burdened by work tasks, might be, for rate of change of acceleration, on the order of 0.05 g/sec, and for maximum deceleration approximately 0.08 g. Based on these values, the idealized onset cue and velocity washout profile can be followed, as illustrated in Figure 28.

Figure 28 shows washout at a deceleration rate below both the deceleration and rate of change of deceleration thresholds. This is continued until just before the deceleration threshold is reached and then the remaining velocity is removed at a constant deceleration below the threshold for deceleration. Curve A of Figure 27 illustrates the distances necessary to produce

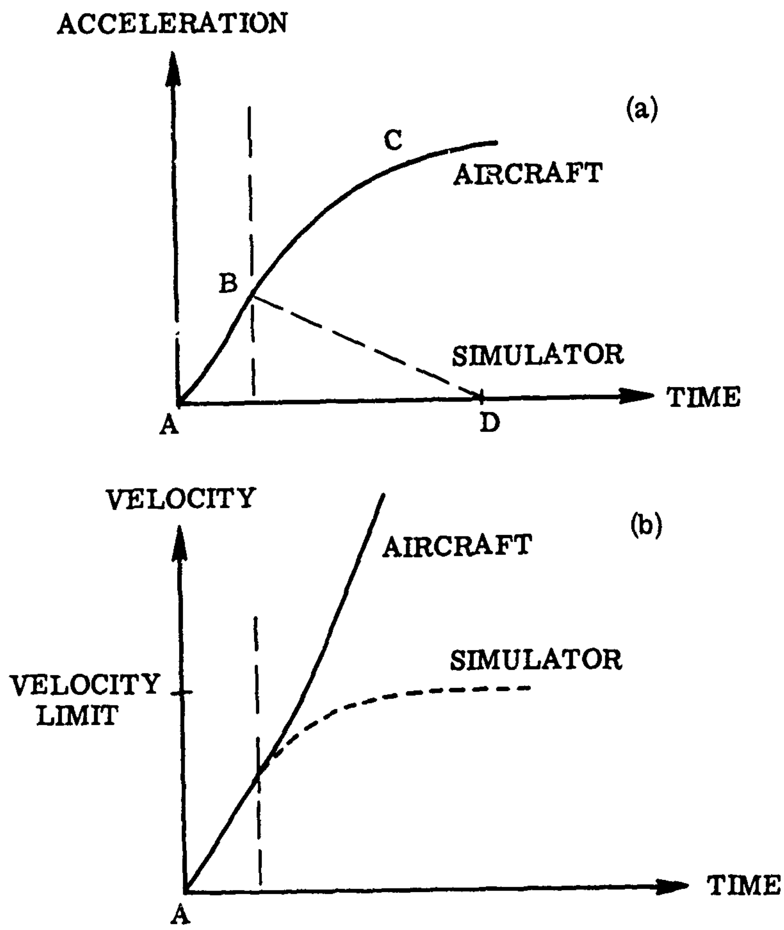


Figure 26 REDUCED ONSET CUE AND VELOCITY PROFILE

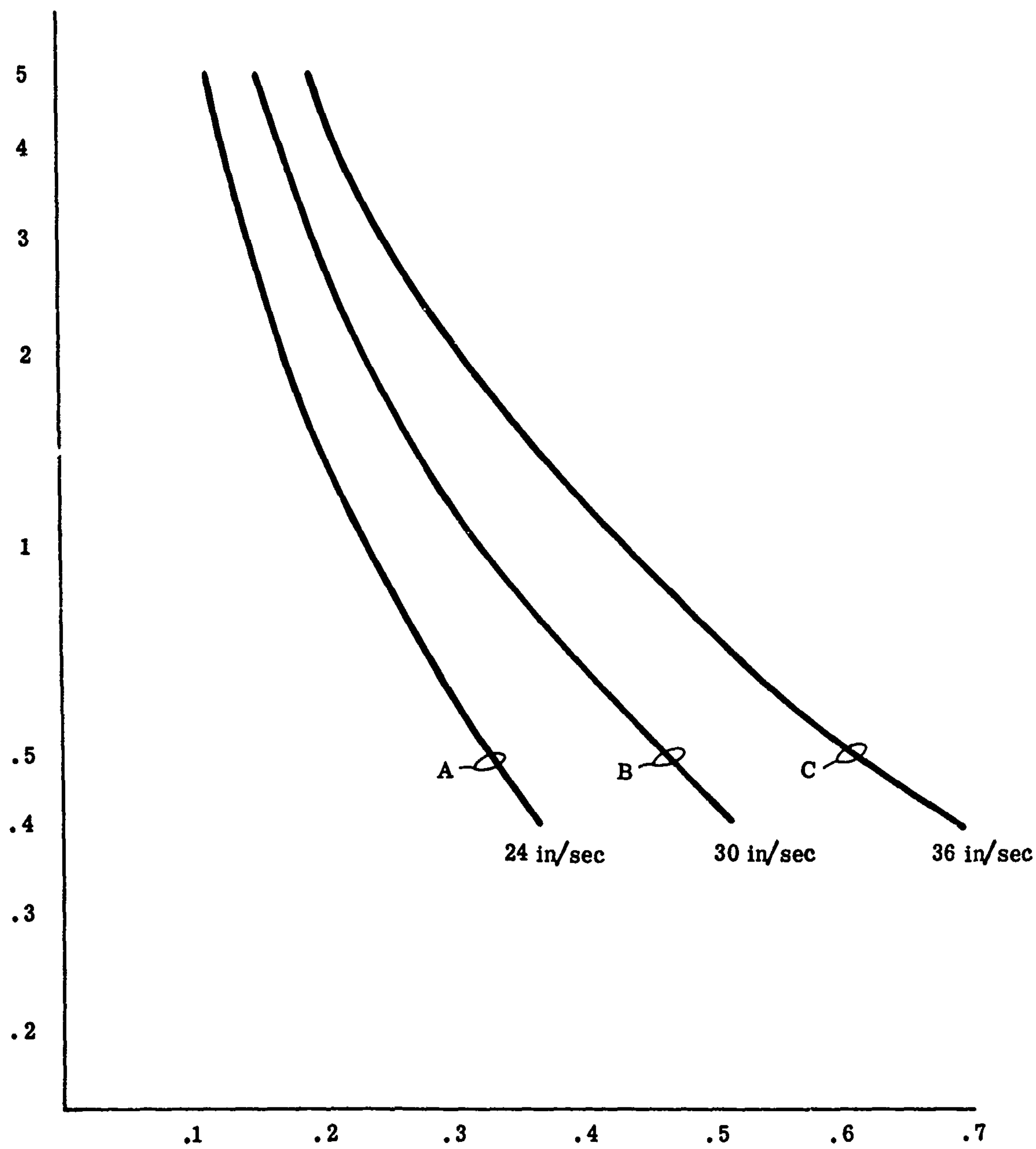


Figure 27 ONSET RATE VERSUS DISPLACEMENT WITH DIFFERENT VELOCITY LIMITS

the range of onset rates of change of acceleration to obtain a translational velocity of 24 inches/second. The longest distances occur with the smallest rates of change of acceleration, and therefore the worst-case excursion requirement will occur with the lowest specified rate of change of acceleration. From the curve, 0.4 g/second corresponds to a worst-case excursion requirement of 4.5 inches. Using the washout profile of Figure 28, the velocity of 2 feet/second may be washed out in a further 19.9 inches. Thus a cue of 0.4 g/second followed by washout requires 19.9 inches plus 4.5 inches, or 24.4 inches. This is true for any system, regardless of mechanical configuration, since these values are referred to motion at the pilot seat. Other examples may be computed using values from Figure 27.

It is evident that greater cue duration can be obtained with high velocity limits. However, there are several inherent disadvantages of systems with larger velocity limits:

1) Larger power supplies

2) The energy to dissipate in the case of failure increases with square of velocity

3) A greater distance is required during the velocity washout phase of the simulator motion as the velocity limit is increased.

8.2.2.4.1 Alternative Approaches to Washout

It is possible to base the design rationale on a scheme that employs a different washout technique or does not employ washout at all.

There are no studies reported in the literature concerning the merits and demerits of various washout techniques. This area of important research interest could be studied in the UPTRSS, to the extent permissible by the facility motion system excursion capabilities. The approach adopted by other vendors cannot be discussed since their responses to a vendor survey provided almost no information concerning their products or design rationales (see Section 14).

8.2.2.4.2 No Velocity Washout

Consider Figure 29. Curve C shows a typical aircraft acceleration-versus-time history (in a single degree of freedom) and Curve A, based on the previous onset cue rationale, shows the corresponding simulated acceleration time history. It is evident that following the first motion cue, maximum velocity is reached, and without a velocity washout scheme the simulator continues with maximum velocity, imparting no further training until such time as the acceleration becomes negative, forcing a cue in the opposite direction. However, without a scheme for velocity washout, if the

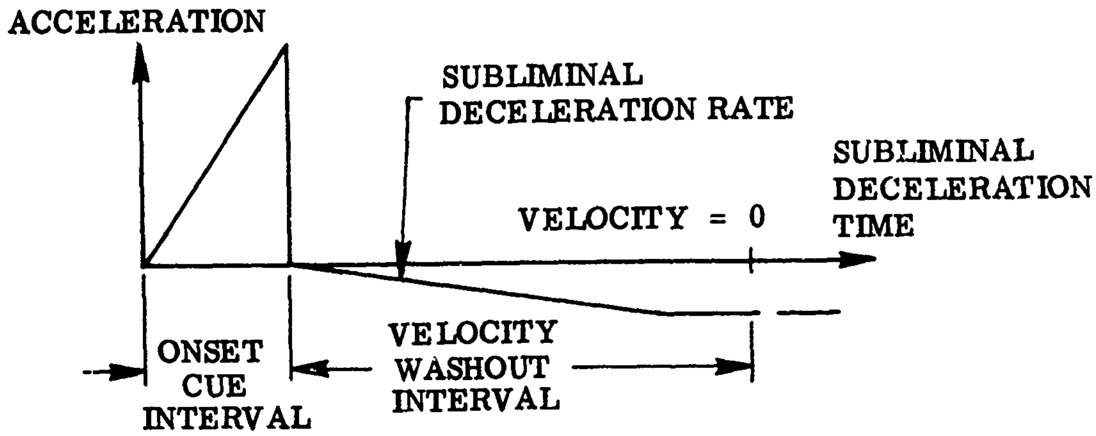


Figure 28 COMPOSITE CUE AND WASHOUT ACCELERATION TIME PROFILE

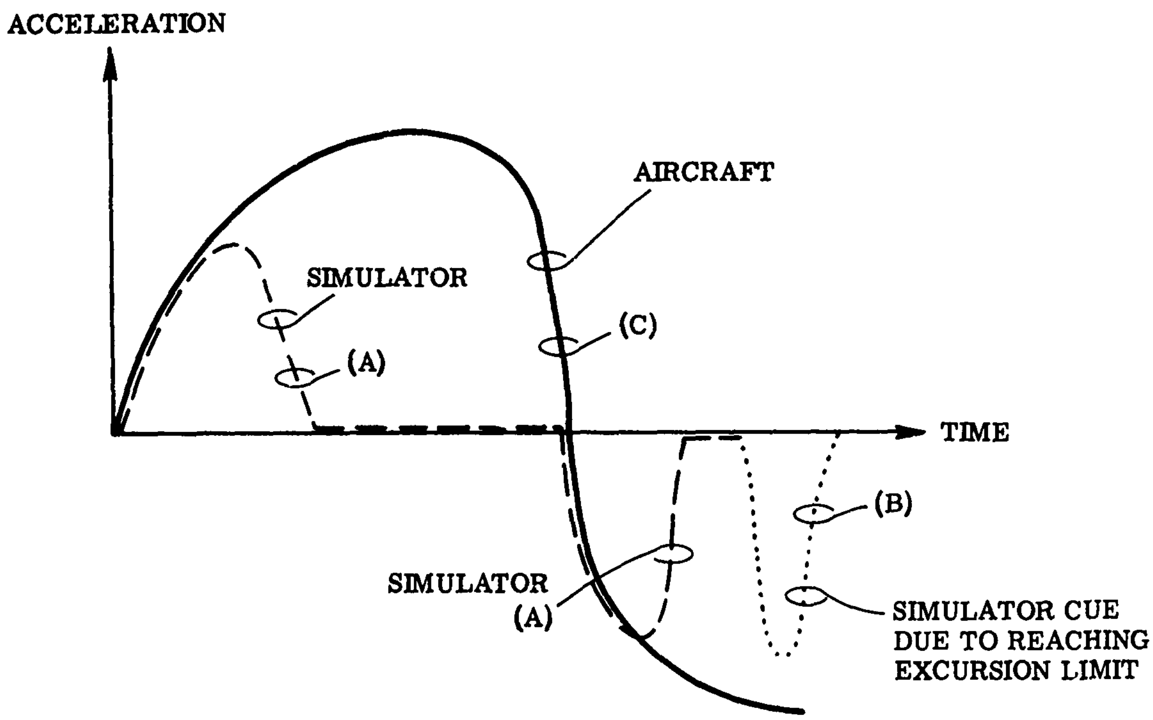


Figure 29 NO VELOCITY WASHOUT

cue in the opposite sense does not occur, and there is no guarantee that a cue in the opposite direction will occur, then the motion system must continue to move until it reaches its excursion limit, in which case a sudden and false deceleration cue will occur, illustrated by Curve B. Thus, a fail-safe rationale must include a velocity washout scheme to ensure that excursion limits are not reached.

An alternative is to make the excursion limits so large that they will never be reached. With 2 ft/sec. as a typical velocity limit, a delay of 2 - 3 seconds can result in additional excursion of 4 - 6 feet before another cue in the opposite sense occurs. This excursion provides no sensation since it is motion at constant velocity. Further, if a cue in the same sense as the original cue occurs, then, since maximum velocity has already been attained, this cue must be ignored. If velocity washout is used, however, this second cue may be accepted because of the reduced velocity. Any approach without washout must be regarded as an extremely costly alternative.

8.2.2.4.3 T-37 and T-38 Translational Requirements

It is evident that as the onset rate increases the displacement requirement decreases (see Figure 27). It is expected that for the maneuvers performed in the T-37 and T-38 aircraft these onset rates will be considerably higher than those normally experienced in commercial aircraft. Thus the excursion requirements for the T-37 and T-38 should be well within the 24.4-inch capability for one translational degree of freedom.

8.2.2.5 Simultaneous Motion System Excursion Requirements

Simultaneous motion is defined as the superposition of motion in one degree of freedom with motion in any other degree of freedom or combination of degrees of freedom. Therefore, any combination of motion in the individual degrees of freedom at any instant in time constitutes simultaneous motion. The preceding discussion utilized a simplified example involving unidirectional motion. This example is significant, however, in that it represents a method of determining a requirement at the pilot's seat and is independent of the geometrical motion system configuration.

It would be imprudent to base the motion system design upon a motion capability requirement derived from the superposition of maximum excursion requirements in all degrees of freedom, because it is unlikely that any maneuver simulated will require all maxima simultaneously. A motion system designed on such a basis would probably be significantly oversized relative to that truly required, with unnecessary penalties imposed in the hydraulic power supply, structural complexity, reliability, etc. Proper sizing of motion system relative to the simulation task necessitates an evaluation of the simultaneous motions experienced at the pilot seat in the most demanding maneuvers, and a determination of the best techniques for providing the necessary motion cues, including washout techniques. The corresponding simultaneous motion excursions represent the simultaneous requirements on which the motion system design should be based.

The following example is intended to illustrate the evaluation process necessary for the definition of excursion requirements. This example applies to a set of commercial aircraft flight maneuvers and must not be considered as quantitatively equivalent to the optimum T-37 and T-38 aircraft requirements.

The evaluation of commercial aircraft flight maneuvers showing a simulated set of maneuvers indicated that certain flight profiles existed wherein the simultaneous motion simulation requirements were most demanding. Such is the case when an engine failure occurs during takeoff rotation. The aircraft at this time is in a high-lift configuration, with landing gear down, high pitch angle, and relatively low airspeed, flight conditions which, if left uncorrected by pilot action, would lead to large accelerations and deviations from the normal flight path. As experienced in the pilot seat, this maneuver produces simultaneous motion cues primarily in pitch, heave, and lateral translation. Figure 30 illustrates a typical time history plot of pitch angle, heave acceleration, and lateral acceleration associated with the failure of an outboard engine of a large commercial transport aircraft at the time of takeoff rotation. The values taken were with respect to the coordinate system of the flight compartment. It should also be noted the plots were based on no corrective pilot inputs during the time span shown, and represent the maximum possible deviations attainable under this particular set of conditions. Yaw and longitudinal motions were relatively small in magnitude compared to pitch, heave, and lateral motion sensations, and can be neglected with respect to motion simulation. Roll appears as small deviations from normal which will not materially affect the following analysis and can therefore be neglected.

The ideal simulation of the extreme maneuver of engine failure at takeoff rotation is illustrated in Figure 31. Pitch rotation should be simulated exactly with respect to its time variation. However, heave and lateral accelerations must be simulated using an onset cue followed by velocity and position washout (return to a neutral operating position). As previously stated, this method of translational acceleration simulation is necessary because hydraulic motion systems suffer velocity limitations. The solid-line heave and lateral acceleration time histories represent the ideal translatory motions that a well-designed hydraulic motion system might employ to simulate the maneuver.

The simultaneous motion system excursions required for the ideal simulation of engine out on takeoff are shown by the combination of the curves in Figure 32. The pitch rotational excursion requirement is identical with that of the actual aircraft. Both heave and lateral excursion requirements result from the double integration of the ideal acceleration profiles with respect to time. They are illustrated by the bottom two curves of Figure 32.

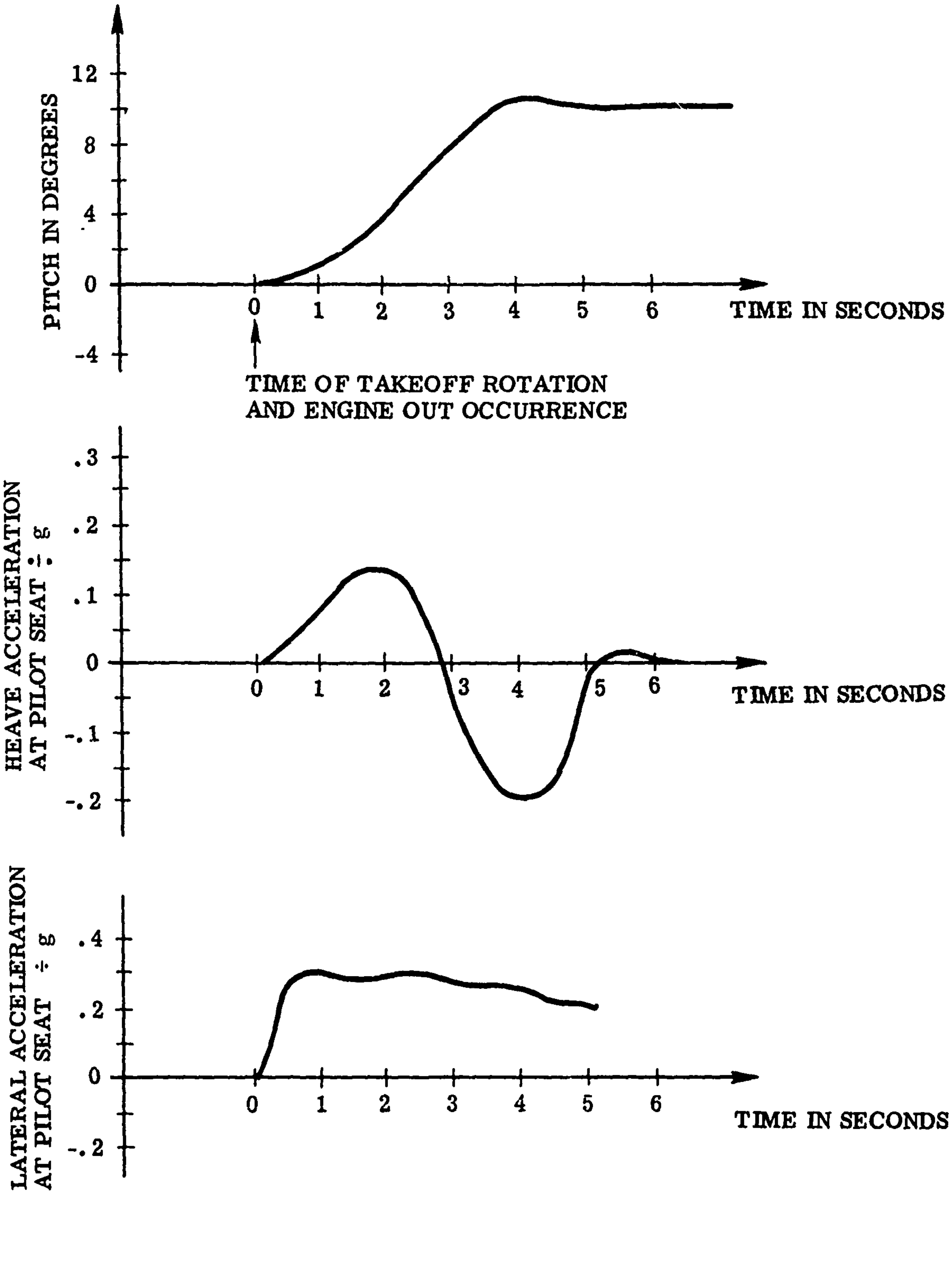


Figure 30 TYPICAL WORST-CASE AIRCRAFT MANEUVER OF AN ENGINE-OUT-ON-TAKEOFF

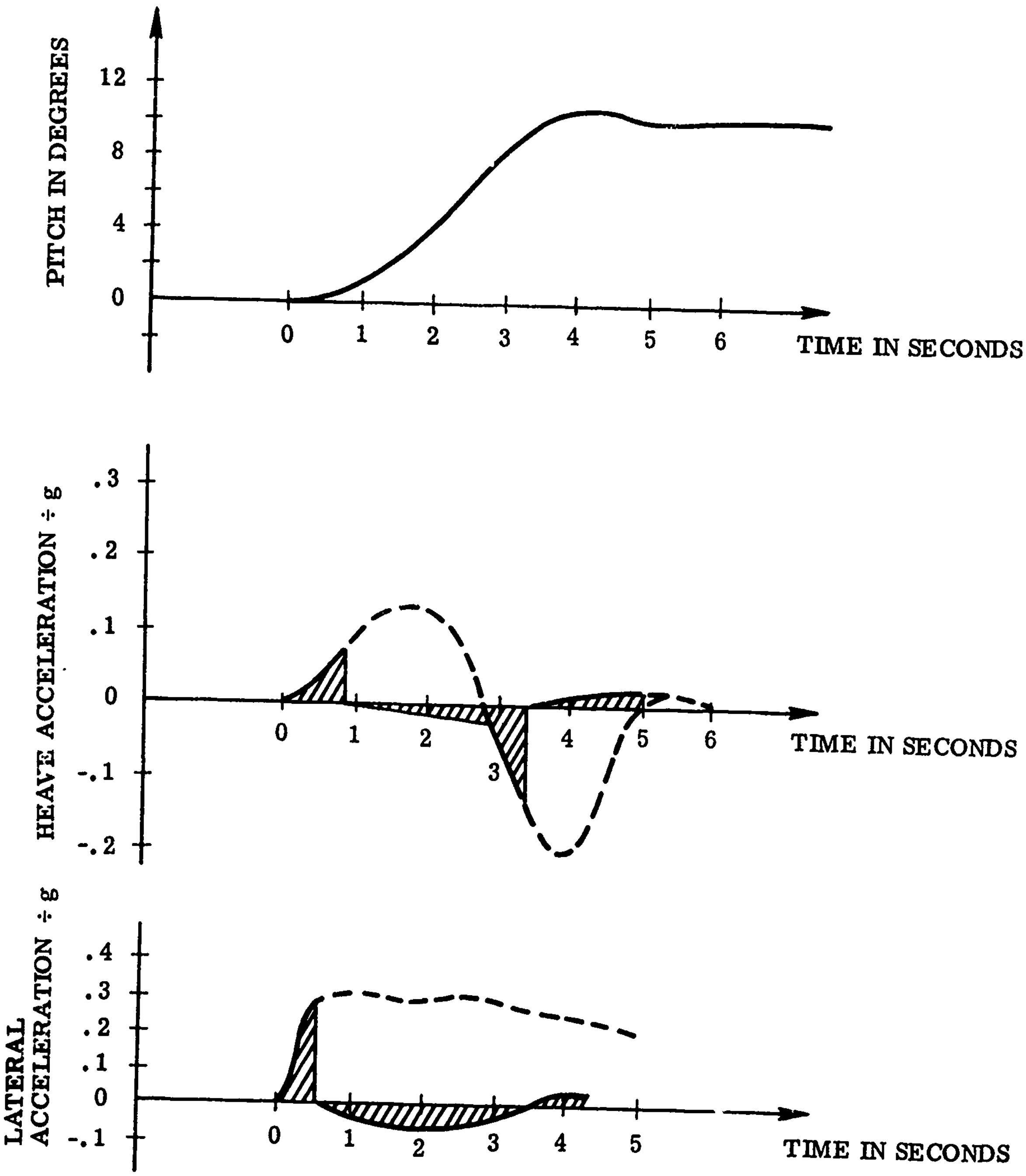


Figure 31 IDEAL SIMULTANEOUS MOTION SIMULATION OF AN ENGINE-OUT-ON-TAKEOFF MANEUVER AT PILOT SEAT

Since the simultaneous requirement is the summation of all the instantaneous, individual excursion requirements, it changes as a function of time for any maneuver. The greatest excursion requirements for the engine-out maneuver occur near the time t_1, about 2 seconds after engine failure at takeoff rotation. At this instant, a motion system must possess the capability of translating approximately 25 inches in the lateral direction, 24 inches in the vertical direction, and 5 degrees in pitch rotation. However, this set of excursion requirements is only representative of an engine-out simulation in one direction. In general, the motion simulation should be symmetrical with respect to the lateral direction, in order to accommodate ideal simulation of either a right or left outboard engine-out maneuver. The simultaneous excursion requirements should then be ±24 inches of lateral translation, simultaneous with 24 inches of heave and 5 degrees of pitch, relative to a given operating neutral position of the motion system (e.g., "wheels on ground" neutral position).

As the time from engine failure proceeds, the simultaneous excursion requirements keep varying. At t_2, about 4 seconds from engine failure, the simultaneous requirements are 11 degrees of pitch with -8 inches of heave and ±5 inches in the lateral direction. These simultaneous motion requirements are those which are necessary to perform a worst-case maneuver.

As stated previously, the function of the example presented was to illustrate an approach to the selection of excursion requirements, using a particular cue and washout rationale being implemented on current six-degree-of-freedom systems. The excursions developed in this manner do not depend upon the geometry or capabilities of an existing system; however, since the rationale is based on human-factors information and practical hardware considerations, the rationale assumes that the velocity limit is reached before the acceleration limitations restrict capability.

The requirements established here reflect the training program needs for commercial aircraft. Considerable attention has been given to simulating engine-out maneuvers which produce severe lateral and yaw motions and have often led to accidents during the in-flight training of these maneuvers. The large lateral and translational motion system requirements that results from this are felt to be capabilities in excess of the T-37 and T-38 requirements. However, there would appear to be no disadvantage in this, since flexibility is the very keystone of the UPTRSS requirement, and the need to be able to change drive signal formulations and rationales for the control of the motion system may lead to larger excursion requirements.

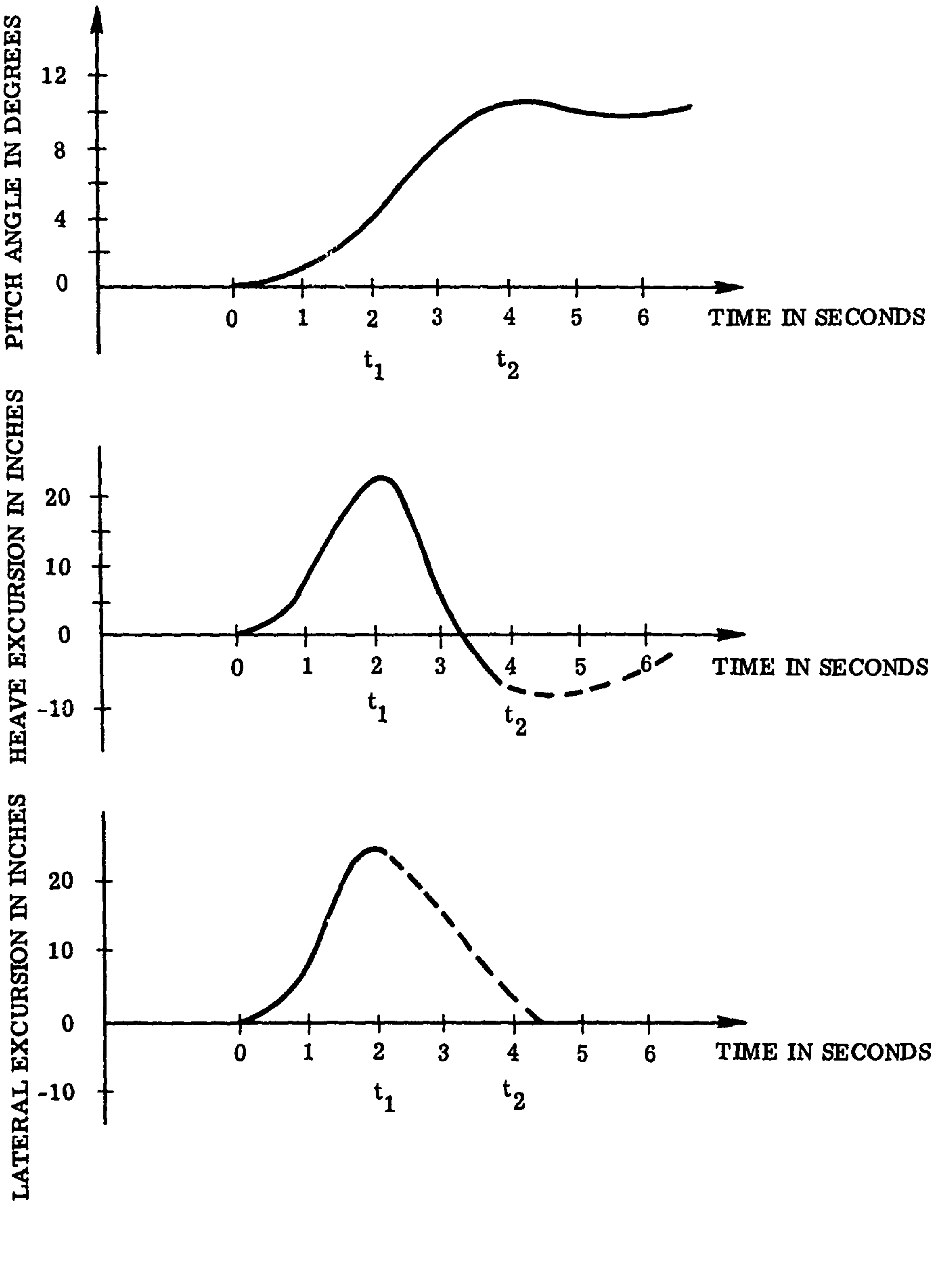


Figure 32 IDEAL SIMULTANEOUS EXCURSION REQUIREMENTS FOR ENGINE-OUT-ON-TAKEOFF SIMULATION

8.2.3 Motion System Control Loop

A motion system simulation capability is directly related to the bandwidth of the frequency spectrum of the motion system control loops. The motion system bandwidth, or the frequency spectrum over which the input/output relationship of the motion system control loops is approximately unity, should be equal to or greater than the frequency spectrum of the drive signal. Only then will the commanded motion sensations be fully experienced by the trainee. A motion system bandwidth less than the signal spectrum will result in attenuation of the high-frequency components, producing more sluggish motion than desired.

In addition, system natural resonant frequency must be controlled. With sufficient damping, resonances are easily excited, leading to undesirable motion system oscillations. Generally, very high-frequency resonances, say at the 50- or 100-hertz level, need not be very heavily damped and do not present a problem. Conversely, resonances at 5 hertz and below can be quite evident, and without a high damping ratio will seriously degrade the performance of the motion system. Furthermore, these low-frequency resonances generally represent a limit to the bandwidth that can be achieved in the control system. As a consequence, the natural resonances of the structure and drive components of the motion system represent very definite limits to the fidelity of the overall simulation, and both frequency and damping ratio must be kept as high as possible.

8.2.3.1 Primary Limitations

The basic parameter to be established in designing a motion system is the type of drive device. In general, this will be dictated by the dynamic capabilities — response time, force (or torque) characteristic, velocity capability, etc. — of the available devices and the requirements of the simulation task. The types of simulators which provide motion cues for personnel training generally involve loads ranging from 1,000 up to as much as 20,000 pounds. In addition, the drive equipment must have very rapid response time, so as not to place a low-frequency restriction on the bandwidth which can be achieved in the entire motion system control loop.

Motion systems may be powered by a variety of power sources, such as electric motors, pneumatics, hydraulics, and magnetic devices. The motion-producing devices which have proved to be most successful for the larger systems have been powered by hydraulic actuators. Electrohydraulic servo systems possess all of the features required for simulator motion system prime movers: high power output in a relatively small package, relatively silent operation, high speed of response, and excellent controllability at very low signal power levels. Electromechanical or other devices cannot, at this time, compete with the hydraulic devices in any of these respects.

8.2.3.2 Hydraulic System Characteristics

Among the various hydraulic systems available, linear actuators have found most frequent application. The linear actuator is easily controlled, and avoids most of the problems of backlash, deadband, and cogging which frequently degrade performance in rotary systems.

The pressure drop across the controlling servo valve is given by:

$$\Delta P = K \frac{Q^2}{A_v^2}$$

where Q represents flow through the valve orifice, A_V is the valve orifice area, and K is a constant which includes the effect of fluid density. Since pressure within the chamber decreases from source pressure by the pressure drop across the servo valve, total force capability, hence acceleration capability, will decrease by the square of piston velocity.

The natural resonant frequency of the motion system will be the composite effect of mechanical resonances of the structure and that of the drive system. The latter is due primarily to the compressibility of the hydraulic fluid, and with proper mechanical design will generally be the dominant effect. There exist systems in which the mechanical resonances have been deliberately permitted to be of the same order as the hydraulic resonances, but these have required particularly sophisticated feedback compensation techniques for damping to provide smooth operation.

The hydraulic natural resonant frequency is given by:

$$\omega_n = K \frac{A^2}{MV}$$

where: ω_n = natural resonant frequency (in radians/second)

A = piston area

M = load mass

V = volume of entrapped fluid

The parameter K includes the effects of hydraulic fluid bulk modulus and technique for servo valve connection. Load mass can be replaced by inertia, with an appropriate modification of the coefficient K.

The volume of entrapped fluid is approximately

$$V = AL$$

where L represents the length of the fluid column. This approximation neglects the effect of fluid in the lines from valve to actuator, but this is generally a small quantity compared to that within the actuator itself. It is evident, then, that an increase in actuator length, in order to achieve greater excursion capability, will result in a decrease in natural resonant frequency. Increasing the piston area will increase the resonant frequency, but at the price of increased flow requirements.

8.2.3.3 Compensation

An increase of complexity of the trainer, in the interest of achieving a more realistic simulation of the operational environment, leads to a potential degradation in motion system performance by increasing the total load, thus decreasing natural resonant frequency. As in most physical systems, a reasonable compromise can and must be achieved between these separate interests.

Typical systems show natural resonant frequencies on the order of 1-10 hertz. Those in the lower portion of this range must be well damped in order not to degrade overall motion performance, and generally require an additional means of system compensation. Velocity and pressure feedback techniques have been used frequently for increasing system damping. The former technique must be carefully implemented in order to avoid the effects of gear noise and backlash. Pressure compensation, which derives the compensating signal by sensing pressure variations within the chambers of the hydraulic actuators, has been used with considerable success with a variety of systems. It is more easily implemented by using electrical techniques, rather than hydraulically compensating the servo valve, because the electrical approach permits exact adjustment to a desired level of performance on the actual machine, as well as the ability for modification in the event of a large change in load. The acceleration feedback compensation technique is less frequently used, because it is more difficult to implement properly. It has been used effectively in systems including quite poorly damped mechanical structures, with the mechanical resonance enclosed within the acceleration compensation loop. Care must be taken, however, that factors such as centrifugal acceleration and variations in gravity vector relative to accelerometer axis of sensitivity do not degrade the technique excessively.

In addition to the problem of damping, system natural resonant frequency can present a limitation to the overall control loop bandwidth which can be achieved. Past motion systems have not required bandwidths much in excess of 0.5 hertz, but the more sophisticated drive signals developed recently may well require bandwidths in excess of 1 hertz. Apparent

system bandwidth may be increased in some instances by using a drive signal representing the motion desired, but including additional signals to emphasize the high-frequency characteristic. These supplementary inputs generally include weighted first and second derivatives of the basic drive signal. Although this approach can significantly increase apparent system performance, it has inherent in it the ability to drive the control system more easily into saturation, so its use must be carefully evaluated to achieve the desired results.

8.2.3.4 Signal Data Rate

One other parameter must be considered in the effort to maximize system bandwidth, namely input signal data rate. For simulators driven by digital computing systems, the sampling theorem places an upper limit on signal bandwidth equal to one-half the output iteration rate. As a practical matter, the output iteration rate should be at least five, and preferably ten, times greater than the system bandwidth to prevent its effect being felt through the motion system.

Typical computer complexes provide a motion-system signal data rate of approximately 20 iterations per second, implying that a practical motion system bandwidth need be no more than 2-4 hertz. Whatever the output data rate, an apparent increase can be achieved by delaying the drive signal by one iteration and then interpolating as frequently as required between the most recent and the first preceding computations. This approach, of course, introduces a lag in the drive signal of one computational cycle, so the opposing effects of data granularity and lag must be weighed against one another to provide the best compromise for the particular application.

8.2.4 Desirable Motion System Features

The operation and maintenance requirements of simulator motion systems should be made as simple as possible. Emphasis should be placed on the practicality and inherent economic advantages associated with the simplicity of the system designs mechanically, electrically, and hydraulically. It is most desirable that the simulator operator have to perform a minimum effort in turning the system on or off and that there be no questionable method of achieving the desired results — i.e., no special manual operation of switches or sequencing should be required of the operator.

The following discussion is divided into five subject areas which, taken together, form the total suggested requirements for an integrated simulator motion system operation. The five subject areas are:

1) Desired operational features

2) Electrical control design considerations

3) Mechanical design considerations

4) Hydraulic design considerations

5) Safety

8.2.4.1 Desired Operational Features

The intent of the suggestions listed below is to provide a simple, foolproof system by which an operator may control the turn-on/off of the motion system without the need for special procedures.

1) The motion turn-on control should be under the control of the simulator operator from a single master location, usually at the operator's console.

2) Sufficient interlocks should be provided for the simulator with all canopies or entrances to the simulator flight compartment wired in a holding-type electrical circuit which prevents the turn-on of the motion system by any switch except the master motion control switch but which will automatically terminate motion when opened. These interlocks should work in conjunction with the master motion control in the following manner. Arming of all the interlock switches in the simulator complex is required to make the simulator ready for motion use and thereby arms the master motion control switch so that the motion may be turned on or off at any time by the operator. The opening of any interlock will constitute a motion abort procedure and automatically terminate motion in the normal manner the same as if the master motion control switch were placed in the "OFF" position. Closing of any of the interlocks immediately after opening will not reinstate the motion operation, but will require that a recycle of the master motion control switch be performed by the operator in order to re-establish motion system operation. This type of circuit operation provides for the authority to ensure that only the simulator operator will be capable of turning the motion system on while allowing the authority to the trainees to terminate the motion at their discretion.

3) As a minimum, the interlock switches should be provided at the following locations:

a) Cockpit canopy

b) Cockpit entrance stairway or gate

c) Personnel protective skirt, removable maintenance sections, and simulator nose cowlings

d) Inside the cockpit accessible within arm's reach to the pilot

e) Underneath the cockpit at a convenient location on the motion base frame or at a location external to the cockpit for maintenance purposes. A key-operated switch is most desirable for the maintenance function to prevent unauthorized persons from tampering with this interlock when maintenance is in progress.

4) If the simulator is equipped with a primary control loading system which is capable of having its force-producing mechanism shut off so as to relieve all control forces, the primary controls electrical turn-on circuit should be interlocked with the master motion control switch to prevent the possible application of step inputs to the motion command amplifiers by sudden unrestrained control movements. Simple spring-loaded primary control systems need not be interlocked with the motion system since the loading of these systems is constant.

5) If a great number of interlocks are used in the simulator, annunciator lights should be provided, either at the operator's station or at a maintenance panel, which indicate the interlock switch position, i.e., canopy open, maintenance in progress, etc. These lights will serve to assist the operator.

6) The combined operation of both the motion system electrical circuits and motion servo power control system should provide for the ability to turn the simulator motion system "on or off" at any time regardless of cockpit position, attitude, or computer condition — i.e., no constraints should be placed upon motion system turn-on or turn-off by any of the other simulator complex equipment. Electrical control power and/or hydraulic power ready should be the only constraining sources for the simulator motion system.

7) The turn-on/off systems should provide for a gentle turn-on/off of the motion system, free from shocks and abrupt movements of any axis of the motion system and minimum dynamic capability. Proper control and automatic sequencing should be provided to allow the dynamic capability of the motion system to gradually be increased to its maximum smoothly and without step inputs or abrupt positional changes in any of the axes of the system.

8) An emergency stop system should be provided to quickly terminate the motions and automatically return the motion system to its "at rest" position. The system should be implemented electrically and mechanically "fail-safe" in the event of power loss to the simulator.

8.2.4.2 Electrical System Design Considerations

The following considerations apply to electrical system design:

1) The design of the entire electrical system should be consistent with good electrical design practices, with particular regard to proper shielding of all signal lines and grounding of return paths so as to minimize the effects of electrical noise and/or spurious emissions of other electronic equipment, either internal or external to the simulator complex.

2) The electrical system should provide interlock circuits for all the necessary power and reference voltage sources, implemented in holding-type circuits so as to provide for an automatic shutdown of the motion system in the event of any single failure of any of the reference power supplies or complete loss of power to the simulator.

3) A suitable electrical detector system should be provided in the protective circuit networks to automatically terminate the motion of all of the prime movers of the motion system. This device should cause an electrical "null" effect to be present at the servomechanism prime mover such that no shock is created nor a runaway type of servo failure results from either loss of simulator power or any of the servo system reference voltages.

4) If many interlocking circuits are used in the simulator, annunciator lights should be provided at a maintenance panel suitably located in the simulator complex so as to indicate the operational status of the strategic logic control circuits.

5) The implementation of all electrical interlocks or emergency-off switches and motion command signal circuits should provide for smooth switchover capabilities so as not to produce transient step inputs to any of the motion servo systems as a result of the operation of any of these devices, relays, etc.

6) It should be possible to control the turn-on/off of the motion system without the necessity of having the simulator computer in operation. This feature is important for maintenance purposes and provides the basis for isolating the motion system operation from the simulator computer complex. This feature will assist in the maintenance and troubleshooting of both the motion control system and prime mover system without introducing any possible undesirable effects which might be generated by the computer.

7) A motion control maintenance panel should be provided as part of the simulator, suitably located at a position where the

operation of the motion system may be observed by the operator. This maintenance panel should provide means to perform the following functions:

*a) Hydraulic or electrical servomechanism power-on control

*b) Motion on-off control

c) An independent manual/automatic selector control for each servomechanism used in the motion system

d) Servomechanism position readout indicators for each servomechanism in the motion system

e) Annunciator lights indicating the operational status of strategic parts of the electrical and/or hydraulic power systems

f) Suitable jack-type test points for strategic points of the motion electronic control system so as to provide easy access for hookup of test instrumentation without the danger of shorted circuits due to hanging test probes in the electronic bins

8) The motion turn-on/off and sequencing system should preferably be controlled by an automatic analog-type electrical device to provide the necessary motion turn-on control signal attenuation commands without requiring the simulator computer for control. This device should be implemented in a manner that makes it "fail-safe" for reset purposes in the event of loss of electrical power to the simulator.

9) The servomechanism should be equipped with an automatic limit switch shutoff system to disable the motion system in the event that a servo loop control system malfunction (saturated amplifier effects) causes the servomechanism to exceed its predetermined electronic position limits. Two sets of limit switches should be provided at each extreme position of the servomechanism. The first set is used as a velocity attenuator to cause the servomechanism to slow down. The second set of switches located behind the first should be used as an automatic power shutdown system for the entire motion system.

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* These controls must be arranged in a circuit which provides that the master control be retained at the motion system master control on-off switch.

8.2.4.3 Mechanical Design Considerations

Mechanical design considerations applicable to the motion system are as follows:

1) The mechanical configuration of the motion system should be designed to provide for minimum floor space and ceiling height consistent with the motion system excursion capabilities and type of simulator to be mounted on the moving platform. Installation space requirements should therefore be kept to a minimum.

2) The payload carrying capacity of the motion system should provide for additional weight carrying capacity for the addition of a visual flight training system attachment to the cockpit without any degradation of performance or the introduction of mechanical resonances which could destroy the smoothness characteristics of the motions.

3) The moveable cockpit support platform should be designed as a flat mounting surface for ease of mounting the simulator cockpit and should be capable of resisting all of the static and dynamic loads which will be imposed upon it at maximum control failure conditions by the motion system prime movers. The mechanical safety factor should be consistent with the intended usage but in no case be less than 4 for the worst-case force which can be imparted to any part of the system. The safety factor should be based on the yield strength of the materials used.

4) A level and locked position with respect to the simulator floor should be provided, which in general should be the natural "at rest" position of the simulator, based on the geometry and implementation of the mechanical systems used to provide the motion. Mechanically operated hold-up gates or auxiliary locking devices are undesirable mechanical features. In the event of turn-off or emergency deactivation the motion platform should always slowly return to its level and locked position.

5) Suitable safety precautions and protective devices should be incorporated mechanically and hydraulically or any combination thereof to provide for smoothly arresting the motion system under any worst-case control system loss so as to slowly and smoothly absorb the kinetic energy of the motion system without causing damage to the simulator equipment and/or harm to the simulator cockpit occupants. The type of device used for this purpose should exhibit high reliability with the ability to provide maximum protection consistent with the life of the prime movers of the motion system or within prescribed overhaul periods.

6) The motion system mounting base should be designed to readily mount to a normal-mix reinforced concrete floor with a minimum of effort. No special thick slab sections or pilings should be required for

the installation — i.e., it should be possible to install the motion system in any existing building which has suitable floor space and ceiling height for the simulator.

7) Lubrication provisions should be provided at all movable joints and bearings and should be suitably identified for lubricant type and recommend lubrication intervals.

8.2.4.4 Hydraulic System Design Considerations

The following considerations are applicable to the design of the hydraulic system:

1) The entire hydraulic system design should be based upon using a minimum safety factor of 4 times the operating pressure for all components used in the plumbing system. Hydraulic system pressure should be consistent with the force requirements for the motion system but should not exceed 3000 psi.

2) The hydraulic reservoir should be designed to good hydraulic system practices and utilize a fluid storage capacity of 2 to 3 times the output of the pumping system. As a minimum requirement the reservoir should contain the following items:

a) Access and cleanout provisions

b) Pump suction line strainer, 100-mesh minimum

c) Sight gauge for fluid level

d) Filtered air vent if nonpressurized tank is used

e) Reservoir fluid temperature gauge

f) Temperature limit control switch

g) Baffles (internally)

3) The hydraulic system design should be predicated on minimizing surge and hydraulic shocks within the system, which will be transmitted to the motion actuators. Turn-on/off systems should operate slowly. If solenoid valves are used for this purpose, means should be provided for initially restricting the flow through the valve to minimize the shock created by the rapid opening of this type of control valve.

4) The hydraulic pump should be a variable-displacement type to minimize the heating effect of the hydraulic system at low volume demands of the motion system. The capacity of the hydraulic pump and accumulators should be adequate to supply the flow requirements of the anticipated usage of the simulator. Past experience with other simulators indicates that a pump capacity, with one accumulator in the system, of approximately 25% to 50% of the maximum flow demand for a worst-case maneuver will be adequate for average simulator usage. The higher-percentage flow capacity should be provided for research simulators, where the demands may be the greatest. The actual specification of hydraulic pump capacity should be consistent with the intended usage for economic and maintenance considerations. Hydraulic power equipment and the necessary plumbing accessories are, in general, expensive to procure and maintain.

5) Adequate filtration should be provided in the system to protect the expensive hydraulic servomechanisms from contamination. It is suggested that the following filters be provided in the system:

a) A 10-micron filter in the pump pressure output line

b) A 3-micron filter immediately upstream of each servo valve used in the system

c) A 5-micron filter in the main system return line.

All filters should have an excess flow rating capacity to provide for long operating time between maintenance and should be equipped with a differential pressure switch which automatically lights an annunciator light on a hydraulic maintenance panel indicating a need for maintenance. The switch should also be wired into the pump power control circuit in a manner which will prevent the operation of the hydraulic system if the filter maintenance is not performed. The system should operate in the following manner. During operation of the hydraulic system the differential pressure switch senses the differential pressure across the filter element and when the differential pressure reaches the maximum allowable for effective filtration, the switch actuates and causes the annunciator light to light up (blinking lights or warning horns may also be used) but does not cause the hydraulic power system to shut down. At the conclusion of the training period, when the hydraulic power system is shut down, the electrical logic circuits associated with the filtration system will lock out the hydraulic power circuit so that it becomes impossible to start the pump drive electric motor until the necessary filter maintenance is performed. This type of system automatically prevents inadvertent operation of the system without proper preventive maintenance.

Filter cartridges used in the filtration system should preferably be the throwaway type. Recent investigations into the cleaning efficiency of both throwaway and cleanable filters indicate that the throwaway types are superior in performance. Cost of the replacement element generally is less than the cost of the handling and cleaning of the cleanable types. Also, the cleanable types do not last forever and must eventually be discarded and replaced. The cost of replacement for the cleanable types is generally of the order of 6 times that of the throwaway types. No worthwhile economy is gained by use of the cleanable types and unless cleaning provisions are close at hand, a long turn-around time for the cleaning operation can be expected.

6) The hydraulic fluid used should be a mineral oil type such as MIL-H-5606 B or MIL-H-6083. This fluid is suggested for economy, personnel safety, and maintenance considerations.

While it is generally recognized that a potential fire hazard exists in a hydraulic system which utilizes a petroleum-base hydraulic fluid, the actual experience of the majority of users of ground-based hydraulic systems shows that only in extremely rare instances has there been evidence of fires which could be attributed to the hydraulic fluid. User experience with MIL-H-5606B petroleum-base hydraulic fluid (British Specification DTD-585) has proved it to be completely safe, economical, and convenient to use because of its availability. There have been no reported cases of any simulator having had a hydraulic fluid fire. Over 300 simulators in service for the past 15 years attest to the safe utilization of this fluid.

The suggested hydraulic fluid to be used with the simulator can be readily obtained anywhere in the world at economical prices (the current cost of this fluid is approximately $1.40 per gallon). Also, the amount of experience and test data available for hydraulic components manufactured in the United States indicates that this fluid has met wide acceptance as a standard fluid, particularly in commercial and military aircraft applications.

It is generally agreed that for shipboard applications a fire-resistant hydraulic fluid is desirable. It is also agreed that a fire-resistant hydraulic fluid is desirable for aircraft and "hot" applications such as foundries, injection moulding equipment, heat treating, welding, and mining applications. It is in these critical applications that the use of a fire-resistant hydraulic fluid has been finding wide acceptance. However, it should be noted that a definite need for a fire-resistant system should be firmly substantiated because of the many disadvantages associated with them.

It is conceded that many successful fire-resistant hydraulic systems are in use throughout the world today. The majority of these systems have been specially designed and equipped with special valving

and components which make them compatible with the usage of fire-resistant hydraulic fluids. All of the so-called fire-resistant fluids are only fire-resistant so long as they are carefully controlled. The most successful fluids used to date have been the synthetic phosphate-ester-base fluids such as Skydrol 500, as used in the Douglas DC-8 aircraft, and Cellube 220, which has found acceptance on shipboard installations.

Both of the aforementioned fluids require special design considerations for the system. Some of these considerations are:

1) The use of special Butyl rubber seals and hose material throughout the hydraulic system. This requires that all the system components be specially equipped and therefore become nonstandard items at extra cost and extended delivery cycles.

2) Components must be fabricated free of copper or copper alloys to avoid a chemical reaction with these fluids. This requirement specifically dictates that specially manufactured servo valves be utilized at a tremendous increase in cost. These valves are nonstandard and are not stocked on the shelf.

3) It is anticipated that the life of the pump and components are reduced approximately 25% unless a special effort is maintained to keep the hydraulic system superclean.

4) The need for a superclean system plus the difference is viscosity of these fluids requires that the filtration capacity of the system be increased to at least double the capacity of that required for a petroleum fluid base system.

5) Special paint must be used throughout the simulator complex in the vicinity of the hydraulic plumbing because these fluids are very effective paint removers.

6) The relative cost ratio of the synthetic fluids generally runs 6 to 1 against the petroleum base fluid. Also, the special fluid is not readily available everywhere in the world.

7) The need for special design considerations which must be considered in the initial design of the hydraulic system to accomplish a good working system has been definitely established by the manufacturers of hydraulic power equipment. The nature of these fluids is such that they will seep out of valves and fittings where petroleum base fluids will not. Thus the external leak ratio goes up unless very special precautions are taken in the design of the components and the plumbing system. The cost of normal maintenance is thereby increased. This is not a complete list of the shortcomings of the use of fire-resistant hydraulic fluid, but it does reflect the major areas of concern. No attempt has been made to describe other

types of fire-resistant fluids such as water-glycol or water-oil-emulsion types because these fluids are grossly inferior to the phosphate-ester-base types.

8.2.4.5 Safety Considerations

Among the safety considerations which should enter into the specification of the UPTRSS motion system(s) are the following:

1) Means should be provided to isolate the motion system behind a barrier to prevent personnel from coming into possible contact with the moving machinery during operation. The barrier may take the form of a skirt-type, chest-high enclosure, rope or chain fence, or complete isolation within a separate room for the cockpit and motion system.

2) Flashing red lights or "motion in progress" lights located in the simulator complex indicating that the motion system is in operation should be provided. As a minimum, the lights should be located:

a) Underneath the cockpit motion platform

b) Adjacent to any entrance to the cockpit and/or motion system base

c) At the operator's station

d) In the hydraulic pump room at the maintenance panel

e) On the electronic motion control maintenance panel

3) The hydraulic power unit should be located in a remote location in a relatively soundproof room to remove the noise from the vicinity of the cockpit. A hydraulic maintenance panel should be provided in the pump room for assisting and protecting maintenance personnel. Repeater annunciator lights should be provided at the motion control maintenance panel and/or operator's station for strategic parts of the hydraulic system. The maintenance panel should have, as a minimum, the following readouts and annunciator lights:

a) Hydraulic pressure gauge

b) Hydraulic temperature gauge

c) Low pressure light

d) High temperature light

e) Fluid filter condition light, one for each filter used in the system

f) Power on

g) Maintenance in progress light

h) Motion on

i) Maintenance switch (key operated)

j) Local/remote pump start system switch(es)

k) Low fluid level light

l) Emergency stop

m) Accumulator low precharge light(s)

4) Consideration should be given to the installation of a full-flooding CO_2 system with appropriate automatic sensing in the remote hydraulic pump room. This type of system effects an economy in the installation of the power room and obviates the disadvantage of the flammability of the mineral-base hydraulic fluid.

5) Hand-operated fire extinguishers should be installed in strategic locations in the simulation complex. This procedure has generally been followed in the past for simulators as a general precaution.

6) Adequate training in the operation and maintenance of the simulator hydraulic power and motion system operation. This area has [illegible] been neglected because of the electronic complexity of simulators. Consideration should be given to the training of hydraulic system specialists to assist all simulator users.

8.3 SOFTWARE CONSIDERATIONS

8.3.1 Drive Signal Formulation

The excursions specified for motion systems during the past decade have not in general been the result of long analysis of requirements using modern human-factors research, but have been primarily the result of almost arbitrary specifications, often dictated by unrelated variables

such as available space, funding, etc. Despite this, in nearly all cases a satisfactory motion simulation has been obtained, since the great flexibility of computers enables a variety of software drive signal techniques to be implemented and evaluated.

Typically the drive signal formulation methods have provided an onset cue followed by washout. The washout is generally above subliminal thresholds, and the rationale for the signal formulation is rather unsophisticated in comparison to the discussions of Section 8.2.2.

Despite the simplicity of these approaches, considerable and widespread success has been achieved with their use. A detailed discussion comparing the various simulator manufacturers techniques is not possible since no pertinent information was obtained from the vendor survey (see Section 15). The following equations are typical of the drive signal equations in use, and are employed in Link F-111 mission simulators:

$$\text{Vertical Translation} = K_1 + \frac{K_2 S\,(A_{Z_A})}{K_3 S + 1} + K_4 \dot{q}_a + K_{buffet}$$

K_1 centers the vertical motion, permitting both upward and downward motion. The second term on the right provides an acceleration rate of change in the vertical direction (an onset cue) followed by a exponential washout. The third provides the vertical acceleration at the pilot seat due to pitch acceleration. The K_{buffet} term provides oscillation of varying intensity with vertical direction.

Similar equations with the appropriate aerodynamic parameters exist for the remaining translational degrees of freedom. A typical rotational equation is:

$$\text{Roll Angle} = K_5 + K_6 \dot{p}_a + K_7 \frac{A_{Y_A}}{A_{Z_A}}$$

K_5 centers the roll motion to permit the optimal left and right roll capabilities. The $K_6 \dot{p}_a$ term provides the roll cue and washout, while the last term provides the correct orientation of the gravity vector to line up with the resultant force vector at the pilot's seat.

Similar equations exist for the remaining rotational degrees of freedom.

The advantages of employing drive signal formulation techniques of this form are that they require minimal computer time and storage requirements, and the characteristics of the equations may be easily varied by changing the values of the constants.

Although equations of this type could be employed in a six-degree-of-freedom system, it is worthwhile considering an alternative approach which is based on the principles discussed in Section 8.2.2, and which is being implemented on Link 747 six-degree-of-freedom commercial airline simulators. This system is driven by six hydraulic actuators arranged in pairs. The dynamic capabilities of this system are given in Figure 30.

The motion system drive signal formulation consists of computing the total "sensed" acceleration vector at the pilot's station. This acceleration vector has both a magnitude and a direction. The motion system will simulate both magnitude and direction by first using the motion system's translational capabilities to supply the onset cues. These onset cues give the pilot the sensation of a changing "sensed" acceleration vector for a short period of time (see Section 8.2.3). At the same time, the motion platform is rotated such that the local natural gravity vector approaches alignment with the computed "sensed" acceleration vector at the pilot's station.

By using translational onset cues and rotational gravity alignment, the system simulates both the dynamic and steady-state aspects of the "sensed" acceleration at the pilot's station.

The phasing between the translational onset cues and the rotational gravity alignment is quite easily achieved by generating a first-order lagging function and applying it to each component of the desired "sensed" acceleration vector. The lagging function is used to supply rotational gravity alignment platform attitudes, while the difference between the desired function and the lagging function is used to generate translational onset cues.

The duration of an onset cue is determined by computing a trial value of actuator length for each actuator (a so-called translational go/no-go computation) as if the desired acceleration for a single computational step were accepted, and then the velocity washout (subliminal acceleration profile) were applied until velocity reached zero. Because the velocity washout acceleration profile is an integrable function, the washout time and position can be computed analytically. If the calculations show that any of the actuator lengths would have exceeded allowable limits during the washout phase, the logic discards the desired acceleration and the onset cue is terminated. If none of the actuators would have exceeded their allowable limits, then the trial value is accepted and the next computational cycle is begun.

If the go/no-go computation has reached a "no-go" state, the onset cue is terminated and the velocity washout phase is initiated. However, before proceeding to the next cycle, another check is made to find out whether or not velocity washout can still be accomplished if the gravity alignment is performed (gravity alignment go/no-go computation). If it can, then velocity washout and gravity alignment are performed simultaneously; if not, velocity washout alone is performed.

For the steady-state case, when there are no onset cue demands, velocity and position washouts are performed, thereby returning the platform to its neutral position subliminally so it is ready to accept an onset cue of maximum duration.

As in the previous example, the hydraulic servos are used as position servos whose drive signals are digitally computed.

This technique reflects the state of the art in drive signal formulation. The disadvantages in utilizing such methods are that computer storage and time requirements are considerably larger than before, typically 2,000 words of memory and 60 milliseconds per second of processor time. Iteration rates of 10-20 iterations per second are typical in this application.

The technique discussed is complex, since the motion system is synergistic — i.e., position, velocity, and acceleration capability in any one degree of freedom are limited by the position, velocity, and acceleration in any combination of the remaining degrees of freedom. If each degree of freedom were cascaded and independent, then clearly a much less complex formulation could be developed.

The superiority of the sophisticated technique over the simpler approach described earlier has yet to be verified. Clearly one function of the UPTRSS should be to determine efficient and satisfactory software, by comparative evaluation of various techniques utilizing varying degrees of freedom.

Clearly, with a six-degree-of-freedom motion system it is possible to restrict motion in one or more degrees of freedom and to implement various signal formulations and routines, to evaluate their effectiveness. To enable these changes to be accomplished quickly and easily, spare computer capacity may be required. It might be advantageous to utilize high-level language programming techniques to expedite program changes. Further, it may be desirable to implement various routines which may be controlled by operations at the experimenter's station.

8.3.2 Combining Visual System and Motion System Capabilities

There are several methods of combining visual and motion simulation systems:

1) The visual system projection system and display media (e.g., screen) both mounted on the motion system

2) The projection system mounted on the motion system, and the display media fixed

3) The projection system and display media coupled independently of the motion system

Only in the first case is accurate synchronization of the motion system movement and the visual display possible. Since both projection system and display media are mounted on the motion system, it is only necessary to ensure that the motion cues correctly correspond to changes in the visual scene. It is not necessary to adjust the position of the projection system relative to the motion system. The majority of operational motion/visual systems operate in this manner. In the second and third cases, this adjustment must be made. Synchronizing dynamic response characteristics of visual and motion simulation equipment, to prevent widely different dynamical characteristics from being observed during deviations from the steady state, represents a control problem whose solution, if not beyond the state of the art, presents a formidable engineering task.

In any practical case the marriage of motion and visual simulation systems can best be accomplished by mounting all visual elements on the motion system. This is particularly so if both a complex six-degree-of-freedom motion system and a visual system with the capabilities discussed in Sections 8 and 9 must be incorporated. The third case could be implemented provided the motion system had only small excursion buffeting capabilities, in which case no compensation would be necessary since this visual sensation of motion relative to the horizon would be an accurate representation.

8.4 SYNTHETIC SEAT FEEL SIMULATION

8.4.1 Sustained Acceleration Simulation

The pilot of an airplane is subjected to many sustained acceleration forces during his flight experience. Sustained longitudinal accelerations are sensed during takeoff and landing. In maneuvers such as the loop, the sense of increased force is used as a guide to flying the maneuver. In this maneuver the nose of the aircraft is pulled up until about 3G's are felt. Changes in jet aircraft thrust do not produce high rates of change of acceleration. Thus the sustained acceleration cue provides information which may be interpreted and utilized in controlling aircraft performance.

The lack of simulation capability to provide sustained acceleration environments is a well-recognized deficiency in the overall fidelity of present-day simulators. Progress in the development of reliable and safe hardware has been sadly lacking. While it is known to be impossible to reproduce the acceleration field of the aircraft, knowledge of the critical factors needed to assure positive transfer of training from a simulator to an airplane suggests that if one or more portions of the body are properly subjected to a sustained force, the information, although incomplete, may be of

considerable benefit in improving the training value of the simulator, particularly if these forces are coordinated with the appropriate motion cue simulation.

As stated in the Phase I report, it is possible to provide sustained longitudinal accelerations by pitch rotation of the pilot, provided this rotation is carried out subliminally, and this technique is being employed in state-of-the-art simulators. However, a similar technique cannot be used to simulate lateral acceleration by roll, since side forces are generated which are associated with uncoordinated maneuvers.

In aerobatic maneuvers, continuous positive or negative acceleration act for several seconds, for example in "barrel roll" or looping maneuvers. These sustained accelerations are sensed on many parts of the body such as the head, arms and legs, as well as the back and buttocks of the pilots. There is evidently a requirement to reproduce forces on each part of the body representative of the true aircraft situations.

Various approaches to the mechanization of such equipment were surveyed by Christensen and Johnson in 1958* and essentially little progress in this area has been made since then. This section discusses several approaches to partially and fully integrated sustained acceleration devices. Some of the devices discussed suffer from severe safety limitations and must be regarded as impracticable.

8.4.2 Sustained Acceleration Devices

The effect of sustained acceleration on the various body segments can be produced by three methods:

1) Pneumatic or hydraulically actuated devices

2) Heavy liquids

3) Electrical stimulation of muscles

The following paragraphs discuss these approaches in detail.

8.4.2.1 Pneumatic or Hydraulic Devices

Pneumatic or hydraulic devices can be designed to apply

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* K. K. Christensen and L. L. Johnson "Study to Determine Methods of Simulation of G Effects." Armour Research Foundation of Illinois Institute of Technology, Oct. 1958

forces to various segments of the body. Such devices are shown in Figures 33 and 34. Figure 34 shows an arrangement for simulating positive acceleration forces across the chest. The reaction at the shoulders which does not exist in real flight is minimized by the wide padding. The crossover harness is so designed that movement from side to side is possible. This may be advantageous in simulating forces on the body during sideslipping. The negative acceleration effect is simulated by a separate narrow shoulder strap. When a force is applied by the action of the cylinder, the sensation felt by the shoulder is similar to that felt during negative acceleration maneuvers.

Also shown in Figure 33 is a pressurized variable-area seat cushion. The buttocks is the area of the body which senses most of the changes in weight during maneuvering. The variable-area seat might consist of a relatively hard seat inside of a pressurized pillow type seat, as shown in Figure 34, so that as the positive forces on the chest and shoulders increase, the buttocks will sink into the pressurized seat and contact the hard seat. During negative acceleration forces there is no pressure contact between the buttocks and the seat; thus, the seat could be pressurized to expand, decreasing the force per unit area on the buttocks.

Further sophistications are discussed in Ref. 3 by Christensen. These discussions concern the use of a pressurized waist belt, to move internal organs during negative G effects, to simulate the "pit of the stomach effects," thigh belts, simulation of accelerations on the face, helmet and mask, using a variety of cylinder actuator prime movers. The approaches discussed are feasible provided adequate precautions are taken to prevent personal injury in the event of equipment malfunction.

The major disadvantage of implementing such a variety of devices simultaneously is that the pilot becomes trussed in an unrealistic environment which may result in negative training. There appears to be considerable merit in an arrangement similar to that displayed in Figure 33, from a cost, safety, and simplicity standpoint.

Other systems have been suggested by Flexman, one involving the use of a body lifting harness, another involving the use of pressure pads, applying forces to the back, buttocks, and thighs from variable-displacement seat sectors. Flexman has reported that some experiments were performed in England using a Redifon simulator that indicated an improvement in training when motion of the simulator was accompanied by "G seat" forces. Details of the seat and the experiment are not available.

8.4.2.1.1 Control System

The control system for such devices must be capable of providing accurate magnitude, rate of onset, and decay characteristics with

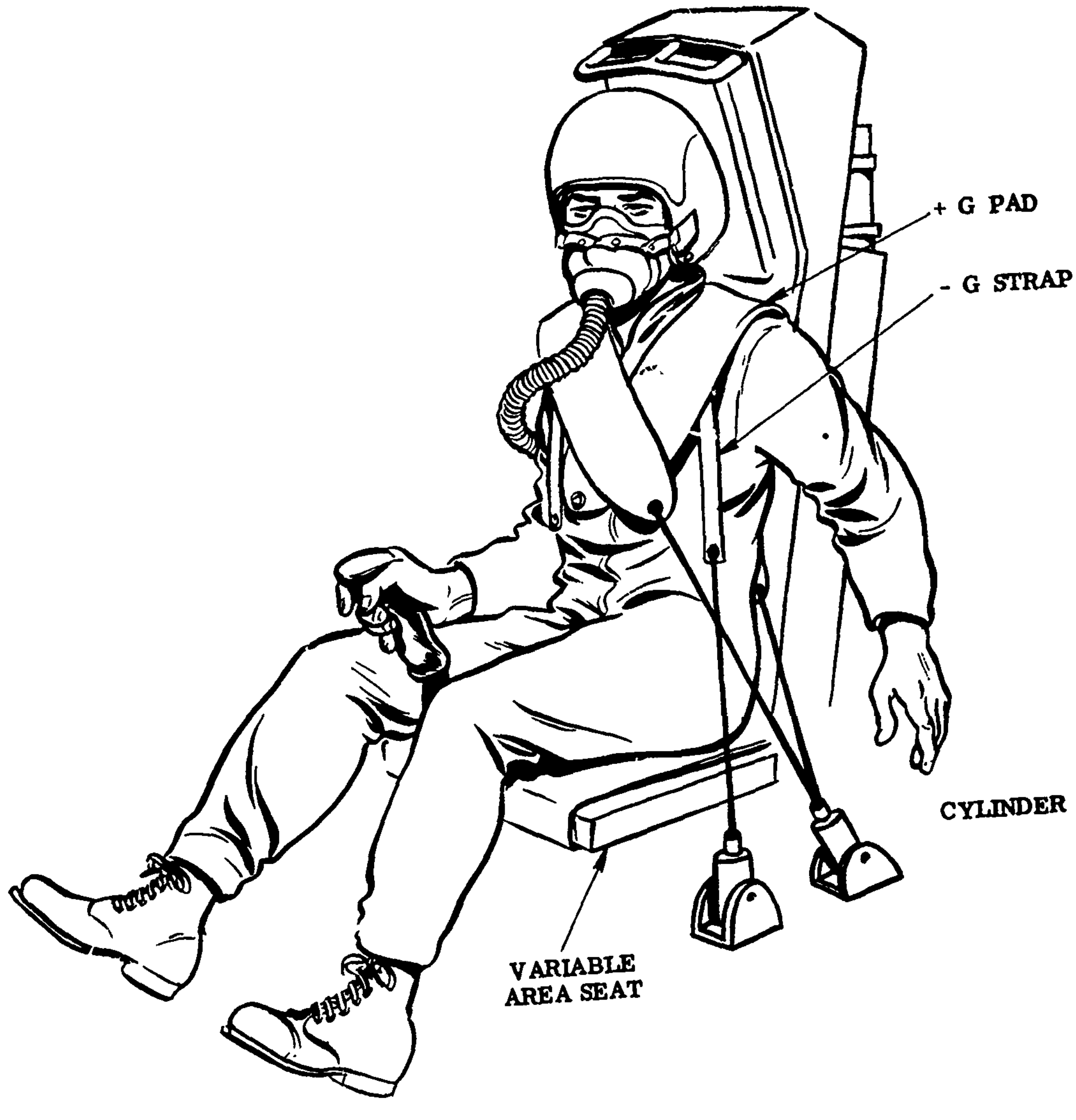


Figure 33 POSITIVE AND NEGATIVE G SHOULDER HARNESS

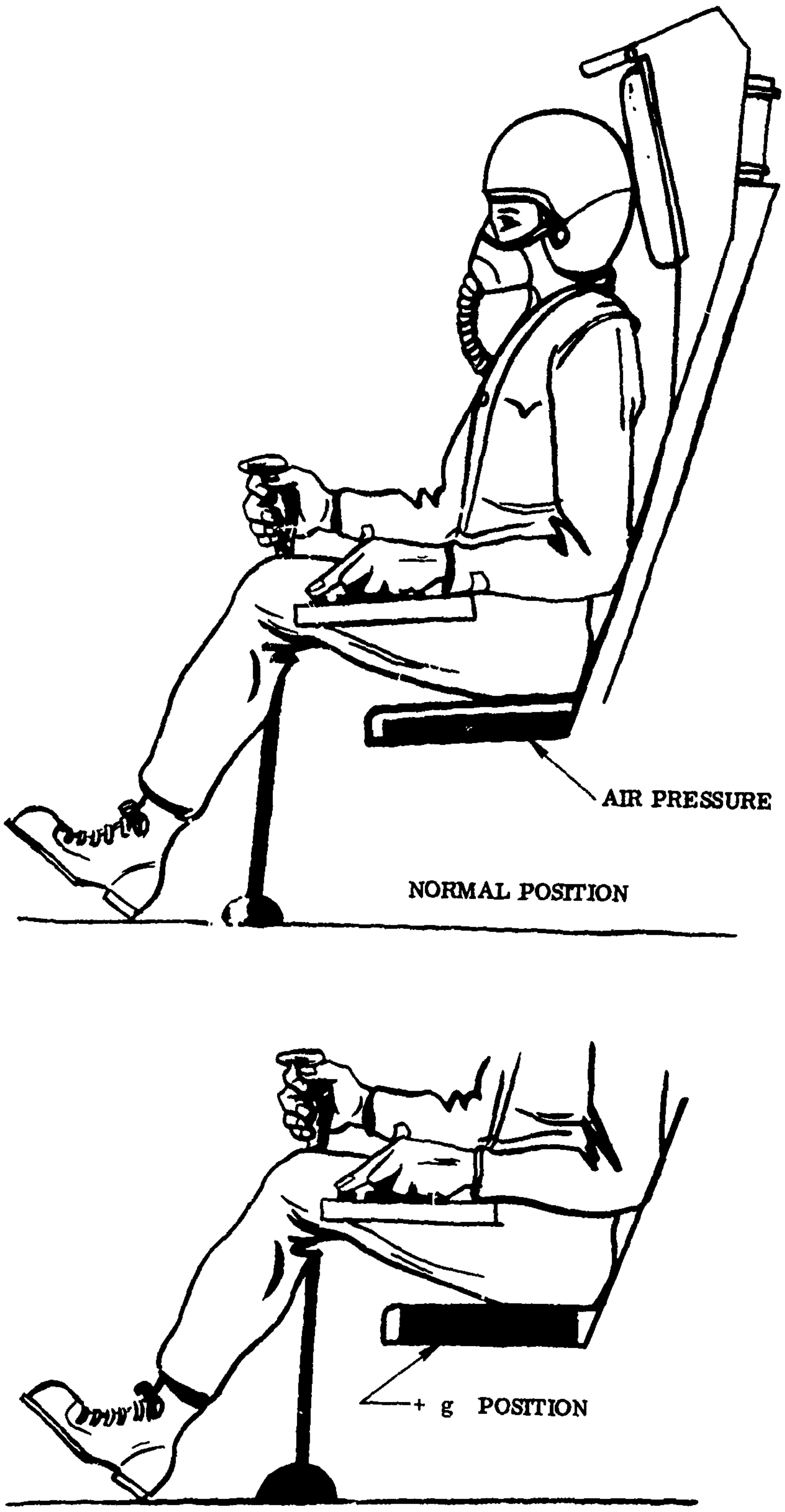


Figure 34 VARIABLE-AREA SEAT

a minimum of time lag to produce or to release forces applied to the body.

8.4.2.2 Heavy Liquids

By pumping heavy liquid (such as mercury), or a slurry (such as lead oxide and glycerin) properly controlled, into various compartments of a double-layered fitted suit, the effect of positive G can be simulated. The approach is beset with numerous technological difficulties, and it does not permit the simulation of negative G effects.

8.4.2.3 Electrical Stimulation of Muscles

A small electrical current produced by a waveform generator introduced near muscles will contract these muscles. In its present form the wave generator technique may be useful in creating certain sensations in the buttocks, and perhaps may be used in conjunction with other devices to help create more realistically simulated G effects.

8.4.3 Conclusion

It is evident that a system of electropneumatic or electrohydraulic devices of the type illustrated in Figure 34 will be capable of producing sensations similar to those experienced during actual aerobatic maneuvers. The use of such a system, together with a six-degree-of-freedom motion system, providing correct onset cues coordinated with the sustained G seat arrangement, should prove of considerable use in improving the training value of motion simulation, while providing a test bed for novel G-seat design modifications. In aerobatic maneuvers, the sustained acceleration capability will greatly enhance the realism. The combination of onset cues and sustained acceleration simulation will tend to decrease the nausea effects associated with uncoordinated motion and visual sensations. Christensen showed further that pilot estimation of forces imparting constant accelerations above 4g is imprecise and thus indicates that simulation of levels above 3g may not be necessary.

8.5 MOTION SYSTEM STUDY RESULTS

8.5.1 Conclusions

From the viewpoint of maximum capability and flexibility it is evident that the primary recommendation must be a six-degree-of-freedom motion system with a G-seat. Considering the relative merits of each of the contributing factors for all phases of flight, it is apparent that an alternative and adequate facility with minimum cost penalty would involve a pitch capability, for buffeting only, plus a G-seat. It would appear to be most practicable to implement a six-degree-of-freedom motion capability with the complete visual system mounted on top of the motion system, except in the case

of a "buffet only" system, wherein the visual system may be fixed to a stationary reference.

Combining the visual specification and the motion requirements, it is recommended that the UPTRSS facility be implemented as follows:

1) Four devices, two T-37's and T-38's, each device having a six-degree-of-freedom motion system with a sustained acceleration simulation device, such as a G-seat.

2) A secondary and less costly recommendation would utilize a "buffet only" system where desired.

3) Programs should be devised to facilitate sensible degradation in performance to six degrees of freedom and from six to five degrees of freedom, etc. Adequate computer capability should be planned. Programs should be devised to determine the requirements for motion simulation, including G-seat utilization for each of the four configurations. These need not necessarily be identical.

4) If an incremental procurement plan is implemented, then it is recommended that at least one complete simulator with a six-degree-of-freedom system plus G-seat be purchased.

5) The motion systems should reflect the recommendations discussed in Section 8.2.3 concerning desirable control loop considerations, and the operational, design, and safety features discussed in Section 8.2.4.

8.5.2 Existing Equipment

As a result of the study and discussions summarized above, it is concluded that the Link standard six-degree-of-freedom motion system will provide sufficient capability to simulate both the T-37 and T-38 aircraft maneuvers while allowing sufficient flexibility to perform research in the areas outlined in the subsections above. This is particularly so if the sophisticated drive signal formulation discussed in Section 8.3.1 and the G-seat device discussed in Section 8.4 are implemented. The capabilities of this system are tabulated in Figure 33.

It should be noted, however, that it is known that several other vendors are producing motion systems with both larger and smaller capabilities than those shown in Figure 35. These vendors are listed in Figure 35; unfortunately, owing to the poor response to the vendor survey and the restrictiveness of proprietary legends, little information could be obtained concerning the rationales upon which these systems are based or their capabilities, and a thorough comparison is not possible. The inexactness of the human-factors information for the simulation of motion

		LONGITUDINAL	LATERAL	VERTICAL	PITCH	ROLL	YAW
LINK (Payload 21,000 lbs)	EXCUR.	+49" -48"	±48"	39" up 30" down	+30° -20°	±22°	±32°
	VEL.	±24"/sec	±24"/sec	±24"/sec	±15°/sec	±15°/sec	±15°/sec
	ACC.	±0.6g	±0.6g	±0.8g	$\pm 25°/sec^2$	$\pm 50°/sec^2$	$\pm 50°/sec^2$
FRANKLIN INSTITUTE		NO AVAILABLE DATA					
CONDUCTRON		NO AVAILABLE DATA					
REDIFON		NO AVAILABLE DATA					
CAE		NO AVAILABLE DATA					

Figure 35 NONSIMULTANEOUS DYNAMIC CAPABILITIES OF AVAILABLE SIX-DEGREE-OF FREEDOM MOTION SYSTEMS

is reflected in the considerable effort that is being expended at research facilities such as NASA-Ames, where research simulators with large excursion capabilities in six degrees of freedom have been constructed. (One device is known to have a lateral excursion capability of 50 feet.)

For the UPTRSS it is important to fulfill a training schedule as well as to perform research, and thus considerable weighing should be given to reliability, safety, and response characteristics (as discussed in Sections 8.2.3 and 8.2.4) in the selection of a motion system. The larger the system capability (whatever the design rationale might be), the more difficult it becomes to maintain, and the greater the hazards. Clearly, a compromise must be made in the selection of any system to be used in the UPTRSS program, in order to maximize both the training and research objectives of the facility.

9. VISUAL SIMULATION

System requirements for visual simulation are the results of the specific application or training function to be accommodated. Proper consideration of this idea is probably the key to achieving optimum visual simulation. State-of-the-art limitations preclude the possibility of achieving the real world as seen by the human eye. Therefore, visual systems must be tailored to the application and the training functions to be provided if hardware feasibility is to be realized and economic considerations are to be fulfilled.

Before considering the various approaches to visual simulation and their applicability to the simulation research facility, some consideration should be given to the capabilities of the final receptor, the eye. The light-sensitive portion of the eye is really an extension of the brain and it has been estimated that 80% of our knowledge comes to us via this route. Visual impressions are integrated, evaluated, and interpreted differently by each individual, thereby rendering visual simulation techniques and requirements prime targets for research studies.

The visual field for a fixed eye (see Figure 36) is approximately 170 degrees horizontal (60 degrees nasal side and 110 degrees temporal side) and 150 degrees vertical (70 degrees up and 80 degrees down).

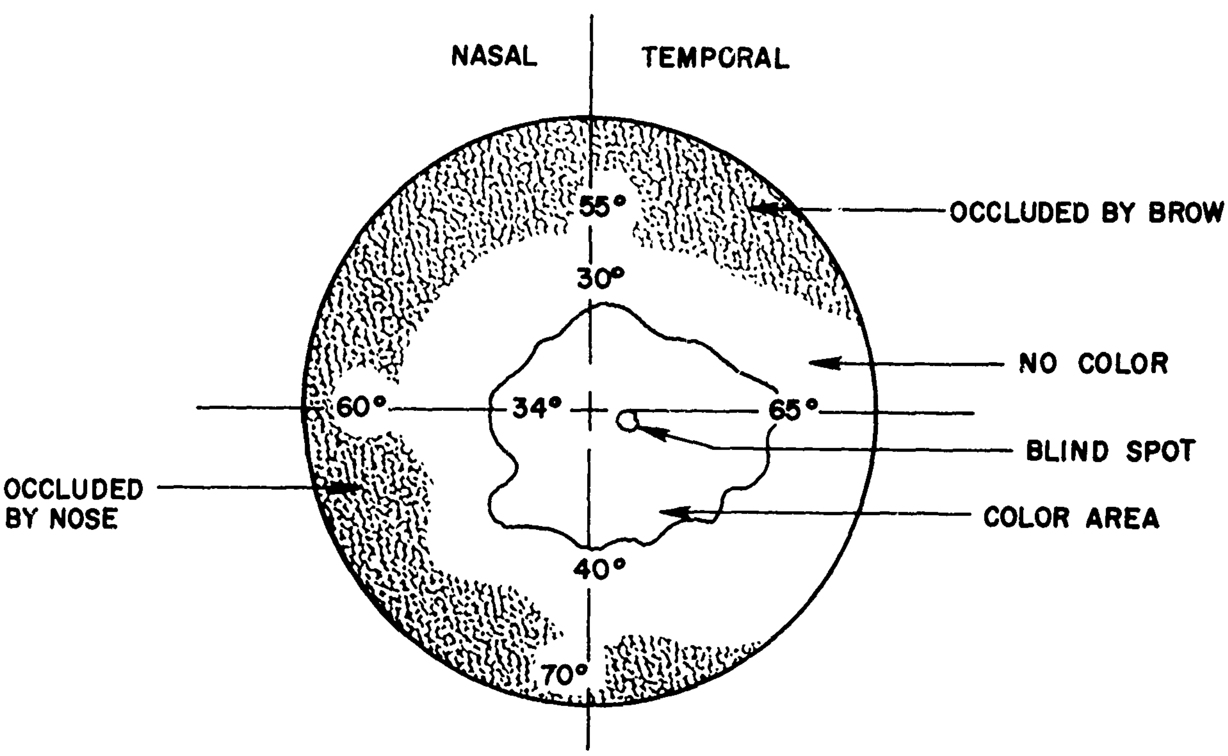


Figure 36 VISUAL FIELD

The area of color perception, however, is limited to approximately 100 degrees horizontal (35 degrees nasal side and 65 degrees temporal side) and 70 degrees vertical (30 degrees up and 40 degrees down). The binocular visual field is normally considered to be 185 degrees horizontal by 150 degrees vertical, with a limited area of color perception.

Convergence is the process of aiming both eyes and focusing on a point. The process of fixating on a new point less than 20 feet distant requires approximately 200 milliseconds; beyond 20 feet negligible time is required to fixate.

Visual acuity means the size of detail that the eye is capable of resolving. The normal measure is in angular terms of minutes of arc. The resolving power of the eye is in the function of many variables such as illumination, contrast, shape, and duration of the stimuli. An object, therefore, may subtend 10 minutes of arc under low lighting intensity to be discernible, while at high intensity an isolated line subtending 1 second of arc is resolvable.

Visual acuity varies as a function of the angular position of the image relative to the fovea (see Figure 37). The realtive visual acuity varies by an order of magnitude between the fovea (0°) and 20° either side of the fovea. The most commonly used measure of visual acuity is minimum separable acuity or gap resolution, which is the smallest space the eye can detect between the parts of a target consisting of alternate black and white equally spaced lines. For a high-contrast target and background brightness exceeding 1 foot-lambert, the acuity of the eye is approximately 1 minute of arc. Other measures of acuity are:

1) Minimum perceptible acuity — This is a measure of the eye's ability to detect an isolated target. Under normal lighting, measurements are in the order of seconds of arc.

2) Vernier acuity — This is the ability of the eye to detect the smallest lateral displacement between two vertical lines without regard to thickness of the lines. Vernier acuity under normal lighting conditions has been measured as 2-3 seconds of arc.

Visual acuity decreases as a function of angular velocity of the target. If a target is moved in the horizontal plane, visual acuity is reduced to 50% by a motion of 60 degrees per second due to motion of the image across the retina.

Relative movement of the visual image may also be introduced by vibration of the aircraft. WADC TR 58-399 notes that "Aside from its annoying and fatiguing effects, vibration has been recognized to impair visual performance in reciprocating aircraft of all kinds, in jets when buffeting occurs,

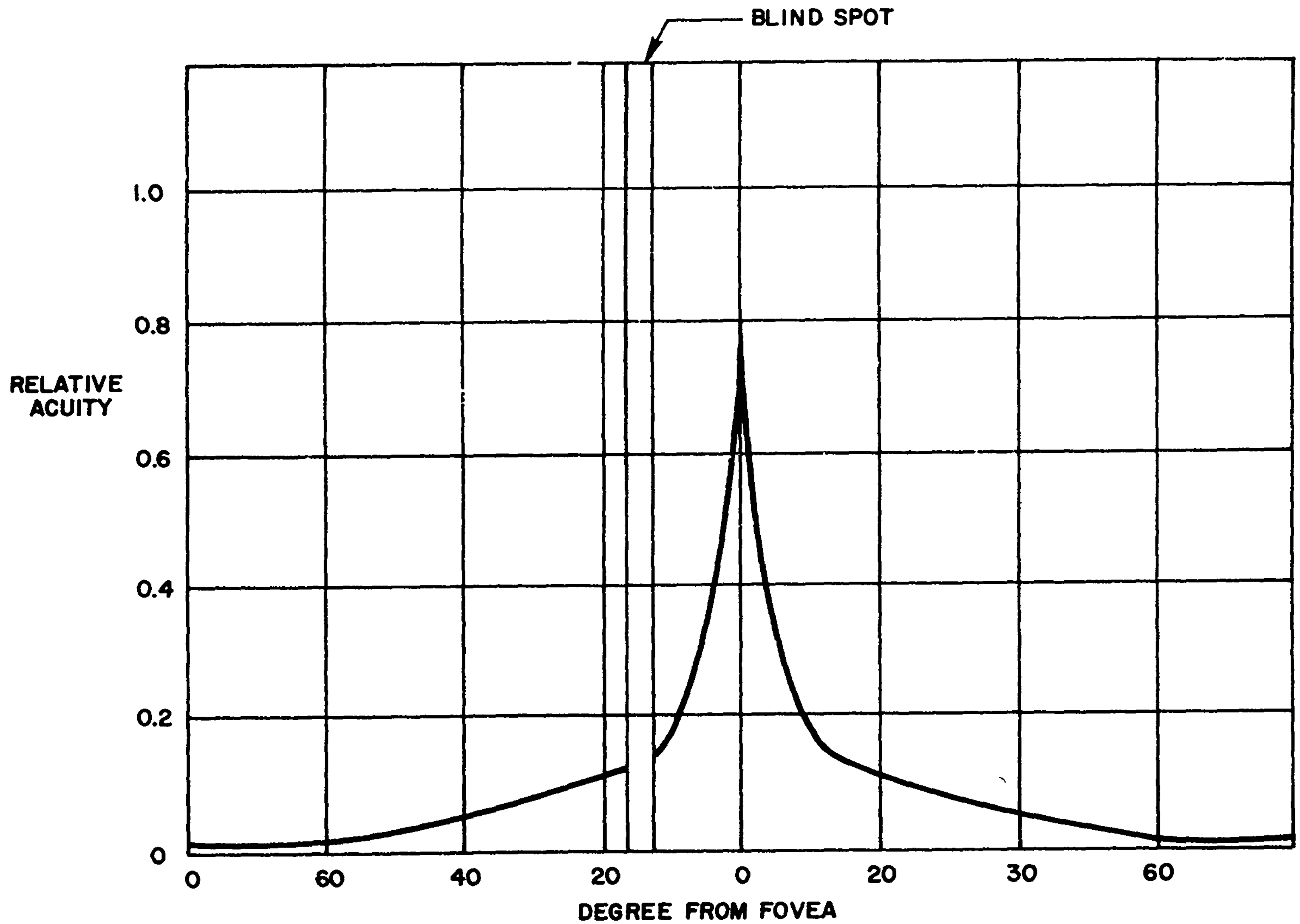


Figure 37 RELATIVE VISUAL ACUITY FROM THE FOVEA

and especially in helicopters." This impairment does not lead to relaxed resolution requirements in visual simulation systems, however, for two reasons:

1) The visual simulation system must function even when vibration is minimal or imperceptible.

2) Simulating the effects of vibration by modifying the out-the-cockpit view is unsatisfactory, since it does not take into account the degradation in the view of the cockpit instruments, and the transmission of vibrations to the pilot's body. Vibration of the trainee station itself is needed to simulate aircraft vibration properly.

In the same reference a set of curves are given which indicate quantitatively the loss of visual acuity as a function of vibration frequency. The worst case studied shows a loss of only slightly over one arc minute in a frequency range from about 20 to 30 cycles per second. This amount is not considered to be of prime importance in most visual simulation systems, however, since the resolution normally obtainable is at least 3 to 10 times this figure. Experimental studies will be required to determine its significance in undergraduate pilot training.

The degradation in visual performance resulting from imperfections (scratches, etc.) in the windshield is generally minimal, since these imperfections are out-of-focus when the pilot is viewing the external scene. These imperfections, together with the border of the windshield, however, might constitute aiming references by which aircraft position and relative motion could be judged, and hence they could pose a stringent requirement for precision of scene position. For this reason, in simulators with visual displays the extra expense of using glass rather than plastic windscreens is often warranted.

The structure of the eye permits visual perception for brightness value of from 10^{-6} to 10^{4} foot-lamberts. This is equivalent to minimal vision under starlight conditions to the brightness of new snow on a clear day. Night vision is considered to be below 0.04 foot-lamberts, which is also th break point for visual acuity. Below 0.04 foot-lamberts, visual acuity de teriorates rapidly from 1 to 15 minutes of arc, with only a factor of ten decrease in brightness.

It has already been pointed out that color stimuli are effective only over a portion of the retinal image, and their contribution as a cue to the overall scene must be evaluated. Aside from the esthetic enhancement, target detection is improved if both high brightness contrast and high color contrast are present. Visual acuity, however, is negligibly improved if high color contrast is added to high brightness contrast. Visual acuity can only be improved by the addition of color contrast when brightness contrast is low.

Accommodation is the process of focusing the lens of the eye on near or distant objects. The near point accommodation varies with age and the elasticity of the lens, but is normally considered as four inches. Objects at distances of greater than 20 feet are considered essentially at optical infinity and accommodation is not a consideration.

A different view of an object is seen by each eye, which provides the primary cue for depth perception. Two objects at varying distances therefore form different angles when viewed independently by two eyes. These differences in convergence angles result in stereoscopic vision. As long as this angle exceeds approximately 30 seconds (equivalent to 500 yards range) stereoscopic perception is possible.

The angular positions of real objects when viewed from different eye positions vary as a function of range, and this condition of correct parallax is essential for proper sighting when formation flying conditions are to be simulated.

The eye is truly a remarkable device which, coupled with the computational ability of the brain, provides the human with his most powerful sensor. Since effective simulation to satisfy all parameters of this sensor is a greater challenge than state-of-the-art visual simulation can achieve, proper and careful evaluation of the training function(s) to be accommodated must be the criteria in the specification, procurement, and evaluation of any visual system.

9.1 STATEMENT OF THE PROBLEM

The need for research studies in the general field of visual simulation has been introduced in the preceding discussion. A determination of the areas in which the studies will take place and a general knowledge of the objective of these studies will be necessary in order to delineate the equipment requirements. On the other hand, the visual system limitations and characteristics will impose some restrictions on the degree and type of

research which can be conducted. Certain general areas of simulation research seem almost self-evident, and it is upon these general areas that the visual systems currently available will be evaluated for use in the simulation research facility.

The true value of any training device lies in its ability to impart to the student an acceptable degree of proficiency in performing his required task. In flight simulation the problem is one of teaching a pilot to fly, or to fly better. Determination of the visual system parameters which will provide this teaching most efficiently requires that the visual simulation provided for the UPTRSS encompass the greatest possible number of combinations and permutations of parameters. In addition, it must be possible to vary the fidelity of simulation in image content and quality to evaluate the acceptance level of the student to the simulation provided and the transfer of training which is actually achieved by the parameters involved.

Therefore, the problem undertaken in the visual systems area of this program is the evaluation of the current state of the art in visual simulation equipment as a function of the phases of flight to be taught, and to outline some ground rules for determining the efficacy of various visual systems for a particular intended task.

9.2 SCOPE OF EFFORT

Since the UPTRSS will be used not only to enable an informal choice to be made among various available visual systems, but to specify the performance parameters required of visual systems to be employed in undergraduate pilot training, a discussion of various visual system parameters as they relate to the human visual system functioning is appropriate. These parameters represent those areas to which specifications and numerical values can be assigned in order to provide a basis for an objective evaluation of a device whose acceptability is predominantly subjective.

Those phases of flight in which the Air Training Command is engaged in training undergraduate pilots have been similarly defined and tabulated. For each of these areas of training the visual environment has been defined to the extent of determining as fully as possible those visual cues which are used by pilots in actual flight. This tabulation is used to provide a representative basis for determining the facets of visual simulation which are of true value in flight training.

Cross-reference is then made in the form of a two-dimensional matrix which provides a convenient reference of visual system parameter requirements for each of the "missions" to be simulated. The requirements, as listed, do not necessarily represent the ultimate simulation which might be desired, but rather are intended to represent the minimum performance which should be sought.

Following this is a discussion of current techniques and equipment, their capabilities and limitations, combinations possible, and trade-offs which might be made. These various subsystems are then compared with the requirements previously listed, providing a basis for choosing the visual simulation facilities to be utilized for the Undergraduate Pilot Training Research Simulation System.

9.3 VISUAL SYSTEM REQUIREMENTS

In Section 4.1.1 of the UPTRSS Phase I report, a number of visual system parameters were listed:

Angular Field of View: Vertical
Horizontal

Sharpness: Resolution
Range in Good Focus

Brightness

Permissible Head Motion

Contrast

Color: Presence
Fidelity

Depth Cues: (3D): Monocular Cues
Binocular Cues

Dynamics

Registration and Correlation with Other Cues

Image Distance

Distortions

Absence of False Cues

Scope of Presentation: Altitude Range
Attitude Range
Ground Area Covered
Discontinuities

Repertoire of Scenes

Compatibility with Other Systems (e.g., Motion)

This section will discuss, with respect to the more critical of these parameters, relevant data concerning human visual capabilities, the implication of human visual capabilities for UPTRSS simulator visual systems, and the probable effect on training of parameter values which represent degraded visual system performance.

9.3.1 Visual System Parameters

The visual simulation system parameters which are most commonly specified are:

1) Field of view
2) Resolution
3) Brightness
4) Contrast
5) Exit pupil
6) Image content
7) Range of maneuverability
8) Correlation with other cues
9) Image distance and depth cues
10) Special effects
11) Geometric distortion
12) Perspective

In addition, such descriptions as "realistic scenes" or "real world image" are sometimes added as subjective descriptions indicating the desires of the procuring agency. It is assumed in this study that the measurable, objective parameters will be subjected to the necessary research study in the projected facility to render such nonmeasurable descriptives unnecessary in future procurements or else definable in more explicit terms.

9.3.1.1 Field of View

The field of view of a visual system refers to the horizontal (azimuthal) and vertical (elevation) angles over which the visual scene is displayed. Normally, it is measured from a nominal pilot's eye position and should encompass the total space within which pertinent visual cues may be contained.

Each eye has a field of view slightly in excess of 180°; the fields of view of the two eyes are not identical, and the binocular field of view can be over 200°. This figure is somewhat meaningless, however, since high visual acuity is obtained only in the small solid angle of the fovea, which scans to give a solid angle of high acuity much larger than the fovea itself, but well below the total field of view. This phenomenon of a small solid angle with high acuity surrounded by a large solid angle of inferior acuity has tempted some visual system designers to propose visual systems in which resolution elements are concentrated in the area of foveal vision. Since the eye and head move, this kind of system would servo the sharp area to where the trainee is looking. This approach is theoretically unexceptionable, but no practical way has been found to track the direction of gaze with the required speed and accuracy, and without loading the trainee with sensors that make for a very artificial situation. A variant of this approach is to concentrate resolution elements in the area where the trainee should be looking; this approach gives the trainee a cue, not present in the real world, as to where to look, and is thus unacceptable from a training point of view. As noted in 9.3.1.6, good landings can be made with a 10° x 10° view. It is perfectly feasible to require trainees to become proficient in landings (and other maneuvers) on a simulator with a field of view (and other visual system parameters) far inferior to those available in the aircraft. After demonstrating proficiency on the simulator, it should be easy for the trainee to accomplish the tasks in the aircraft, since the extra cues will be bonuses. The situation is analogous to that of the baseball batter who, after swinging three bats during warmup, finds the single bat he uses at the plate very light and easy to swing. If the validity of this approach can be demonstrated in the UPTRSS, great savings can be effected in visual systems throughout ATC.

9.3.1.2 Resolution

Under normal lighting conditions, an average trainee with 20-20 vision (and undergraduate pilots are selected for good visual acuity) can distinguish lines separated by about 1 minute of arc. A rule-of-thumb criterion among optical system designers is that an optical system must have a resolution capability of 2-3 arc minutes in order to provide a subjectively "good" image. Although a search of the literature has produced no experimental data justifying this figure*, it seems intuitively reasonable that an image of less resolution would be noticeably lacking in fine detail from an esthetic point of view. However, when considering the requirements for visual display systems for flight training, a different frame of

* A study was conducted at Link (reported in Link DLR #609, Analysis of Brightness and Resolution Requirements for Visual Display, 1963; this report is proprietary, and may not be distributed outside the company) to determine the resolution and brightness needed for visual simulation of the earth from orbit; the study was concerned with the acceptability and utility of images of varying resolutions and brightness, and not image quality *per se*.

reference must be adopted in which a "good enough" criterion may be considered based upon the requirements of training rather than esthetics.

As may be noted in Figure 39, the resolution requirements listed range from 3-6 minutes for approach and landing, formation, and night flying to 10-15 minutes for airwork and acrobatics. These listed requirements are based upon the visual cues normally associated with each of the training maneuvers discussed in Section 9.3.2 and with due consideration of the economic cost and possible performance limitations of visual displays designed primarily to provide high resolution. This being the case, it becomes important to analyze the information content of the visual scene, and determine to what extent information needed or used by the pilot is provided (or compromised) by visual systems of various resolutions.

9.3.1.3 Brightness

The human visual system is very poor at making absolute judgements of brightness; for example, the illusion of looking directly at the sun can be achieved with 15 or 20 foot-lamberts after suitable dark adaptation, and although the human eye is extremely adaptive to differences in brightness of the scene being viewed, there are practical constraints on the minimum light level at which a visual system may be usefully employed.

The inability of visual simulation systems to achieve real-world brightness has four implications:

1) Since flicker fusion threshold is a function of brightness, and increases with increasing brightness, the frame rate need not be as high for less bright images.

2) Color sensitivity curves differ at different brightness levels, so what is realistic color at one brightness level may be unrealistic at another. This effect is probably of little practical importance in the brightness range above 5 or 10 foot-lamberts.

3) Visual acuity improves with increasing brightness. This factor too is of no practical significance in a visual system with a resolution of several minutes of arc.

4) An unrealistic balance of lights inside the cockpit and the brightness of the external visual scene exists. Partial compensation for this can be had by dimming all lights inside the cockpit, but a proper balance often makes these lights (e.g., instrument-illumination, map lights, CRT's) too dim to see properly. There is also the problem of color balance, since much of this lighting is incandescent and can be dimmed most easily by operating at lower voltages, which results in a definite shift of the light to the red end of the spectrum.

9.3.1.4 Contrast

Contrast is defined as the difference between the luminance of an object and the luminance of the surround divided by that of the surround. At any given brightness there is a minimum contrast which is discernible. As shown in Figure 38, detectable contrast is approximately constant from about 0.5 to 30,000 foot-lamberts at a value considerably less than 0.1. However, this curve represents the minimum detectable contrast rather than one that might be considered comfortable or easily discernible. Additionally, the visual tasks involved in aircraft piloting, unlike those of image interpretation, often involve the recognition of abrupt contours, such as runway boundaries, and hence the true value of contrast and gray scale limitations are not easily evaluated.

The contrast discussed so far refers only to relative black and white. Naturally, color contrast can be added to this as a second dimension. If color is utilized, the relative brightness of adjacent differently colored objects becomes of lesser importance so far as distinguishing or resolving them is concerned unless the brightness difference is very great.

The variation and evaluation of both color and brightness contrast on the general acceptance and effectiveness of a visual display could be the subject of some very fruitful UPTRSS research.

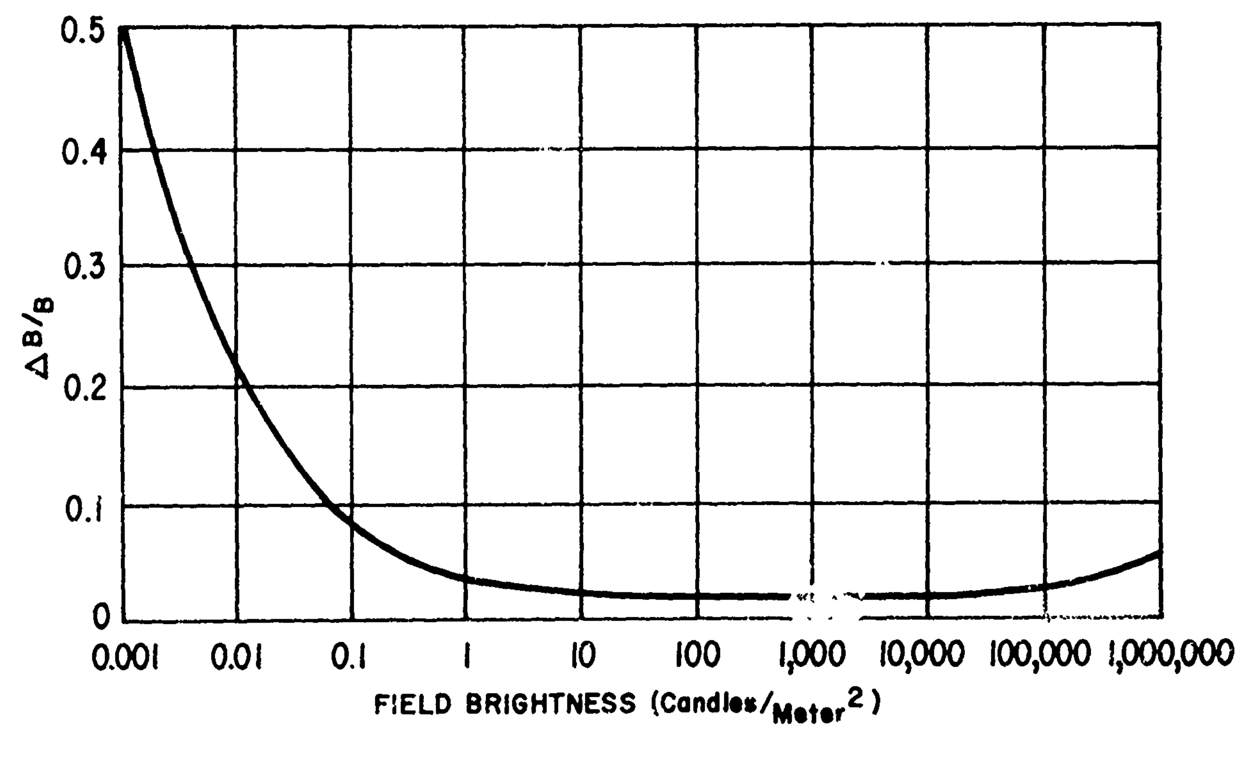


Figure 38 VARIATION OF CONTRAST SENSITIVITY WITH FIELD BRIGHTNESS

9.3.1.5 Exit Pupil

The exit pupil defines the volume of space over which the displayed image may be viewed by the observer. The exit pupil of any visual simulation system must obviously be sufficiently large to encompass both eyes of the student pilot when seated in a normal position. Further extension to include normal head motion during flight is also considered necessary when related to an active feedback simulator where pilot participation and resultant reaction are included in the training since it is most undesirable to allow trainees to make responses different from those desired in the operational situation. He should also be permitted freedom of seat positioning in the simulator, so he sits in the same relative position as in the aircraft.

The availability of the display to an outside observer, such as an instructor, is also highly desirable, although perhaps not mandatory, and the availability of an extended exit pupil may be dictated by economic considerations as well as by technical limitations.

9.3.1.6 Image Content

As used here, image content refers to the type of image contained in the display, as well as the information density, the extraneous and incidental scenery, and the realism imparted to the display, regardless of the techniques used to generate it.

The type of image defines the scene as being, for example, an airport for takeoff and landing, other aircraft, general rural or urban terrain, horizon, etc. The quantity and type of detail included in the displayed image combine to determine the total image content. Variation of both quantity and type would seem to be necessary to determine the actual training requirements and transfer of training evaluation studies. Unfortunately, in spite of considerable study (see, for example, Lybrand, W. A. et al., Simulation of Extra-Cockpit Visual Cues in Contact Flight Transition Trainers), the visual cues that are used (as contrasted with being needed) in contact flight are rather poorly understood.

Two examples will illustrate this state of affairs:

1) R. E. Flexman et al. (Evaluation of a Contact Flight Simulator When Used in an Air Force Primary Pilot Training Program: Part I. Over-All Effectiveness. AFPTRC-TR-54-38) obtained significant transfer of training with a "tilting blackboard" type of landing display, which basically showed only the shape and position of the trapezoidal shaped runway image.

2) S. N. Roscoe (The Effects of Eliminating Binocular and Peripheral Monocular Visual Cues upon Airplane Pilot Performance in Landing. Journal of Applied Psychology, Vol. 32, No. 6. December 1948, pp. 649-662) showed that good landings could be made with a monocular 10° x 10° view.

Obviously, pilots utilize cues they do not really need. The value of providing these used, but not really needed, cues in a training situation will undoubtedly be studied in the UPTRSS.

9.3.1.7 Range of Maneuverability

The range of maneuverability incorporates the ground area covered with terrain detail plus the altitude and rotational degrees of freedom provided and any restrictions imposed upon them. The research studies will presumably help to determine the required excursions in each of the degrees of freedom for any particular training program, but in the determination of required values for the visual simulation, some values have been listed in Figure 39 which are considered nominal minimum values.

9.3.1.8 Correlation With Other Cues

The response of the visual display to control action taken by the pilot and the correlation of image motion with the simulated aircraft response is unquestionably quite important. The response must accurately simulate in position, rate, and acceleration that which would occur when actually flying in order to avoid the introduction of negative training cues. The degree of inaccuracy permissible before such negative training is obtained is anticipated to be a subject on which research studies will be performed.

Similarily, correlation of visual system response, motion cues, and instrument indications must be obtained in order to provide positive training transfer, and system response in each of the three areas must be variable to permit a determination of the degree of correlation required.

9.3.1.9 Image Distance and Depth Cues

It takes a pilot some 0.6 seconds to shift his focus from the instrument panel to the out-the-window scene (infinity) and back again. If the simulator visual system employs a TV monitor as a display device, or otherwise places the display close to the plane of the cockpit instruments so that little or no refocusing is needed, the training situation becomes easier than the operational situation, a most undesirable state of affairs. Another undesirable aspect of close-in displays is the improper parallax perceived when the trainee moves his head, or shifts from looking with one eye to looking with the other. For these reasons, an infinity-image display

system is desirable; however, a screen 10 feet distant is, as far as accommodation (focus) is concerned, practically at infinity, and produces tolerable parallax discrepancies, although minimally so, for most phases of flight.

Except for formation flight, the closest object viewed by the pilot is hundreds of feet away, except during the final phase of landing (by which time the merit of the landing has already been decided) and during taxiing. Hence, binocular depth cues — retinal disparity and convergence — are of negligible importance, and the monocular cues — size, interposition, etc. are the only depth cues used. Thus, if the geometry of the area covered is properly represented in the visual display, the appropriate visual depth cues will be available.

9.3.1.10 Special Effects

As used here, special effects refers to the introduction of variations in visibility caused by variable weather conditions. Conditions ranging from unlimited ceiling and visibility to zero-zero weather can be simulated with varying degrees of realism by almost any of the visual systems available today. The primary area of study anticipated in this area is the effectiveness of the various methods and perhaps a determination of whether or not such special effects really contribute a significant amount of training value at all.

9.3.1.11 Geometric Distortion

The size and shape of objects seen in the visual simulation system must not only appear correct in a static situation, but must not change perceptibly as their position in the visual field changes as a result of simulated aircraft motion. This dynamic requirement is much more stringent than the static one, since the eye is quite sensitive to small changes. Thus, although a 10% to 20% geometric distortion might not be disturbing nor even noticeable in a static display, in flight training visual simulation where dynamic displays are the rule, the geometric distortion must be held to about 2% or less to prevent detectable image distortion effects, and to less than about 5% to prevent disturbing effects. This is a general requirement which will apply equally to all simulated maneuvers.

9.3.1.12 Maintaining Proper Perspective

In order to realize the maximum benefit from a visual display system, it is necessary that the scene be presented with a reasonably proper perspective. That is, the scene must appear to have proper size and spacing relationships between parts of the image as they would appear from the spatial position and orientation being simulated. A striking example of incorrect perspective occurs frequently in televised baseball games in which the pitcher and batter are viewed through extreme telephoto

lenses from center field. The small angular field of view and size of the players makes it appear that the picture was taken from an infield position, but the nearly identical size of the players and the apparently foreshortened distance between them belies this assumption. Since one of the primary cues for depth perception in a two-dimensional visual display is that of relative size, the maintaining of proper perspective in a flight simulation display is very important.

9.3.2 Flight Training Areas

The areas of flight in which the undergraduate pilots receive training have been defined within the following categories:

1) Taxiing
2) Takeoff and climb-out
3) Approach and landing
4) Airwork and aerobatics
5) Formation flight
6) Navigation
7) Night flight
8) Instrument flight

The following discussion outlines the visual environment and cues normally believed to be associated with training in each of these areas.

9.3.2.1 Taxiing

The visual cues normally associated with teaching a student to taxi an airplane such as the T-37 or T-38 are similar to those visual cues which are used in learning to drive — that is, the appearance of the ground or taxiway in front of him, plus the peripheral stimulation of other aircraft, either stationary or moving, and learning the response of the craft to his manual controls. In order to simulate this, it is desired that a large peripheral field of view be supplied in which various objects may

be made to move or to be stationary. Potential collision problems should be presented to the student and reasonable freedom of movement over the taxiway should be available.

9.3.2.2 Takeoff and Climb-Out

In order to take off from a standing start the pilot must taxi at least part of the length of the runway at constantly increasing speed, recognize when the plane has reached rotation velocity, and then rotate the plane prior to his climb. The first phase of this operation is similar to the taxiing maneuver, except that presumably he does not now have to worry about collision with other objects and is concentrating primarily on maintaining a straight line down the runway. His instrumentation provides him with information as to when he has reached proper speed for rotation, and in rotating, the visual cue most readily apparent is that the horizon disappears below the nose of the airplane. For this phase of the simulation, the visual requirements are quite simple in that the primary interest of the pilot is focused on the area straight ahead of him down the runway and he is very little concerned or interested in what may occur in his peripheral vision. The apparent movement of the horizon toward the nose of the ship merely confirms what he should have expected to happen. Therefore, a moderate field of view of about ±90° horizontally and about +15°, -30° vertically directly ahead of the pilot would seem to be sufficient to give him the information necessary to watch a realistic picture of the runway pass under him and for the horizon to move downward, although of course a full peripheral scene availability would be desirable in order that the actual requirements might be established by test rather than by assumption.

During the climb and turn out of traffic, the pilot is engaged in such things as adjusting flaps, raising landing gear, and so forth, and the inexperienced young pilot may tend to ignore the possible traffic in the air space around him. Therefore, the visual system which is desired for the climb and turn out of traffic should include a horizon reference and if possible the simulation of other aircraft at random directions and random relative motions within his field of view so that the student does not incorrectly acquire the attitude that his is the only aircraft that is flying. In turning out of traffic the horizon reference is necessary to help the student to control his attitude, and it is also valuable in enabling the student to level off properly when he has reached his cruising or flight altitude.

9.3.2.3 Approach and Landing

Since a vital part of any flight, whether for training or for actual combat, is returning to the ground, the approach to the runway in preparation for landing is required. Since the approach pattern used at UPT bases is a 360 degree turn from over the runway, a great deal of freedom of motion is required by the visual display. In order to faithfully simulate this phase of flight, the visual system must present to the pilot a realistic scene of the terrain below, in and round the airport area. The field of view required encompasses a horizontal field of view of about 270 degrees and a vertical field of view from the airplane structure at the bottom to the edge of the canopy in back of the pilot. This rather large field-of-view requirement is predicated on the approach maneuver, which requires the pilot to fly over the runway, pitch out into a 180-degree turn, roll out onto a downwind leg for a couple of miles, and perform a coordinated turn which will end up with his being aligned with the runway at a distance of about 1 mile and at an altitude of approximately 400 feet. In order to properly perform this maneuver, the pilot will normally use the end of the runway or some other convenient reference point about which he will gauge his turning points, attitudes, altitudes, and position. Since both lefthand and righthand patterns are required for proper training, the field of view must be large enough to accommodate this.

Since it has never been established exactly which visual cues are used in flying approach and landing patterns, it is difficult to predetermine which features must be included in the visual simulation. However, it would seem intuitively obvious that the more nearly the visual display approaches the real-world scene, the better the training capability. As is true in the climb and turn-out-of-traffic phase of a flight, it is also true that other aircraft are likely to be in the same area with the pilot who is attempting to land. Therefore, it would also be desirable to be able to present, in a random fashion, glimpses of other aircraft which are in the area and which might or might not be potential collision dangers.

From the point of final rollout at the 400-foot altitude approximately 1 mile from the end of the runway, the pilot's attention will be primarily focused on the runway ahead where he intends to land and peripheral imagery would seem to be of secondary importance. However, as is true in the case of flying the approach pattern, the more realistic the visual display can be, the greater one would expect the transfer of training to be.

9.3.2.4 Airwork and Aerobatics

The visual cues which are most normally used in any airwork basically consists of the horizon, the wing tips, and a road or a section line on the ground plus a few landmarks near the horizon. In general, therefore,

the visual system used for training of airwork maneuvers should provide a field of view large enough to encompass at least both wing tips and vertically high enough to cover the area directly overhead for use when making Immelman turns, banks, and so forth. The pitch, roll, and yaw of these various landmarks and the horizon are absolutely necessary and the translation and altitude variations are definitely desired if they can be incorporated.

Since in aerobatic maneuvers the aircraft attitude about any flight axis is almost unlimited it is desired that a field of view be provided which is equivalent to that which the pilot may normally see from the aircraft. The visual cues most normally used are similar to those used in the airwork maneuvers, namely the horizon, the wing tips, roads, and other scattered cultural detail on the ground. Therefore, the requirements for a visual system for training in aerobatics are almost identical to those requirements previously listed for the airwork, and a visual simulation system capable of satisfying one requirement may also be used for the other.

9.3.2.5 Formation Flying

In training for formation flight, three items are of basic visual importance: the aircraft on whose wing the student is flying, the horizon for vertical reference, and the other aircraft in the formation. Since formation flights may be to the right or to the left, the relative position of the lead aircraft may appear anywhere from the upper left section of his field of view to overhead and forward to upper right. Furthermore, since the separation of aircraft in tight formation is of the order of 10 to 20 feet (wing tip clearance), depth perception and aspect of the lead aircraft are quite important, along with maintaining the relative position of the lead aircraft in proper position without jumps, wiggles, or other disturbing factors. Except for the student who may be learning to fly lead in formation, the other aircraft in the flight and the horizon reference are considered to be peripheral cues and not of primary importance, although they are desirable.

9.3.2.6 Navigation and Low Level Flight

In order to provide training in flying navigation problems, it is necessary that a reasonably large area of ground be simulated and that the details presented on the ground be numerous and as realistic as reasonable, so that the student may use maps of the type which he will normally use in navigation flights in order to be able to recognize his reference points. In addition, since a student pilot may well stray from his intended course, it is necessary that the terrain coverage be continuous even though he may be well outside his normal allowed avenue of flight. Since the checkpoints used in such flights may not always appear directly under the path of the aircraft, it is necessary that the visible ground range coverage be extended not only forward but to the sides up to at least 60 degrees to the left

and right. At speeds of 400 knots or so, the length of time during which a landmark will stay in the pilot's field of view is quite short — at least for objects which will pass under him. Therefore, the visible ground range available to him should be as great as possible but not less than 5 miles forward and 3 miles left and right, for altitudes above 1,000 feet. The area of coverage should be sufficient to allow at least 10 minutes of flight from start point to a final checkpoint, and longer if at all possible.

The general requirements for low-level flight are similar to those of navigation, in that a fairly large terrain coverage is required for the visual simulation. This is necessary because with a limited area over which a student could fly, he would soon learn to avoid hills and other obstacles by almost reflex action because he has been there before and flown that pattern before. Unlike high-level navigation problems, however, it is not necessary that the pilot be able to observe terrain over large peripheral areas since he is primarily interested in maintaining a correct ground track and precise time of arrival at check points while still avoiding natural features. It is desired that the student be able to fly at altitudes down to 100 feet or less and that the image presented to him contain three-dimensional relief details. The visible ground range available to the pilot in such a flight pattern is directly a function of his altitude and may be simulated as such in the visual system. A reasonable figure for this would seem to be 50 to 100 times his altitude out to a maximum requirement of bout 5 miles. Whatever peripheral scenes can be presented to him would .. beneficial in helping him to establish his relative altitude and velocity and to enhance the feeling of actual flight.

9.3.2.7 Night Flying

When flying at night, standard aerobatics and airwork are not normally performed and navigation is primarily done with the use of instruments rather than by visual means. Therefore, it would seem that only the areas of takeoff and approach and landing would be of primary importance to visual simulation for night flights. In these areas the same general comments apply as for daytime flights, with the exception that at night the color of the lights in the vicinity of the airport is far more critical than it is for daytime, and strobe lights and other visual aids are required to be simulated.

9.3.3 Operator-Instructor Interface

In most flight simulation systems, the visual display subsystem provides a minimum number of controls to the instructor. Except for visibility and ceiling adjustment controls, the visual display is provided with the greatest degree of fidelity possible and malfunction insertion or other system variations are not desired. However, in the use of the visual display as a part of a simulation research facility, such variations in display parameters are quite necessary to facilitate the study, and additional interfacing with the instructor station will be required.

As a parameter or set of parameters of the visual display are varied under the control of the experimenter, it is important that he be able to observe the resultant scene displayed as well as to measure the variable. This implies a possible requirement for a repeater display at the experimenter's station. Further, there is a requirement for operator control over such display parameters as focus, brightness, contrast, etc., which are not normally provided. It should also be possible to degrade visual system performance by the introduction of noise, momentarily interrupting the display, reducing the field of view, etc., from a central control station by means of programming changes or by manual control.

9.3.4 Summary of Requirements

In order to more readily establish the visual simulation hardware requirements for the facility, the parameters and training phases delineated above have been listed in Figure 39 in matrix form. In listing the requirements, the parameter descriptions and values assigned are considered to be minimum requirements for conducting complete research studies in visual simulation. It is obvious that systems which provide more than these minimum requirements are highly desirable so that a greater range of parameter variation can be achieved before running into degradation levels which preclude their usefulness for training, and hence for fruitful study, but technological and/or economic considerations may preclude achieving even these given characteristics.

From the listing in Figure 39, it may be observed that in several areas the required characteristics are very similar for different training phases. Therefore, in determining the facility requirement in the visual area the equipment described will take advantage of as many common characteristics as possible in order to hold the facility costs to a reasonable minimum consistent with the stated intention of not only simulating flight for student training but also for conducting research into the optimum techniques and equipment requirements for simulation. Since there is today no known visual simulation system concept which is capable of providing the equivalent of a section of the real world wrapped in a package and installed on a simulator, it is obvious that some compromises must be made.

PARAMETER	TAXIING	TAKEOFF & CLIMB	APPROACH & LANDING	AIRWORK & AEROBATICS	FORMATION FLYING	NAVIGATION & LOW LEVEL	NIGHT FLYING
Field of View: Up	15°	15°	60°	120°	90°	15°	60°
Down	45°	30°	45°	45°	10°	45°	45°
Left	60°	90°	120°	120°	90°	90°	120°
Right	60°	90°	120°	120°	90°	90°	120°
Resolution (Arc Minutes	5-10	5-10	3-6	10-15	3-6	5-15	3-6 ("point" lights)
Highlight Brightness (Foot-Lamberts)	B >8	B >8	B >8	B >8	B >8	B >8	B >2 (lights)
Contrast: B&W $(\frac{\Delta B}{B})$	25:1	25:1	25:1	25:1	25:1	25:1	25:1
Color	15:1	15:1	15:1	15:1	15:1	15:1	25:1
Image Content • Desired items not required for basic task	Taxiway Structures or obstacles • Parked aircraft and/or ground support equipment • Moving aircraft and/or ground support equipment	Runway Airport buildings and structures Horizon ref and sky •Other aircraft	Runway Airport buildings and structures Horizon ref. and sky Surrounding terrain detail • Other aircraft • Wingtips	Horizon reference and sky Wingtips • Isolated cloud forms • Ground detail Ground references points	Lead aircraft Horizon reference • Other aircraft in formation	Horizon reference Terrain contour and detail correlated with charts and maps Recognizable target or identification points	Horizon reference Runway lighting • Airport facilities lighting • City and other cultural lights • Stars
Performance Range X:	≥ 2 miles of taxiway	≥ 10 miles	≥ 10 miles	Not required	Reference to lead aircraft: 0 - 2 miles	≥ 150 miles	≥ 10 mile.
Y:	≥ 50 feet	≥ 5 miles	≥ 5 miles	Not required	0 - 2 miles	≥ 150 miles	≥ 5 miles
Z (Altitude):	±6 inches	5 ft. ≤ h ≤ 2500 ft.	5 ft. ≤ h ≤ 2500 ft.	6000' ≥ h ≤ 30,000'	0 - 2 miles	100 ≤ h ≤ 10,000 ft.	5 ft. ≤ h ≤ 2500 ft.
Roll:	±10°	-60° ≤ ϕ ≤ +60°	-60° ≤ ϕ ≤ +60°	Continuous	±15°	-60° ≤ ϕ ≤ +60°	-60° ≤ ϕ ≤ +60°
Pitch:	±5°	0° ≤ θ ≤ 30°	-30° ≤ θ ≤ +30°	Continuous	±15°	-60° ≤ θ ≤ +60°	-30° ≤ θ ≤ +30°
Yaw:	± 15°	-90° ≤ ψ ≤ +90°	Continuous	Continuous	±15°	Continuous	Continuous
Response Angular Rates	10°/sec.	60°/sec.	60°/second	90°/second	60°/second	60°/second	60°/second
Translational Rates:	0 - 30 knots	0 - 200 knots	0 - 200 knots	150 - 600 knots	0 - 10 knots (relative to lead)	150 - 600 knots	0 - 200 knots
Special Effects • Desired items not required for basic task	Not Required	• Fog • Haze • Reduced Ceiling • Visibility restriction	• Fog • Haze • Reduced Ceiling • Visibility restriction	Not required	Not required	• Ground fog • Clouds	• Fog • Haze • Reduced ceiling • Visibility restrictions

Figure 39 VISUAL SIMULATION PARAMETERS

9.4 VISUAL SYSTEM DESIGNS

All visual simulation systems require an image generation subsystem and an image display subsystem. Associated with image generation there is also a primary information storage device and possibly information processing. Associated with the display subsystem there also exists, in general, some form of viewing optics. Therefore, the following discussion of systems representative of the state of the art will treat each of these areas on a comparative basis against each of the parameters listed in Figure 39. Basically, the following four approaches to visual simulation have been utilized in existing simulators and will be considered in the subsequent analysis:

1) Model system

2) Film projection

3) Transparency reconstruction

4) Electronic image generation

9.4.1 Model System

This approach to visual simulation requires the construction of a scale model of the scene to be simulated. A TV camera or some other kind of optical pickup is placed on a complex of gimbals and servomechanisms located over the model. As the pilot operates the controls in the aircraft simulator, the camera scans the model and a picture of the model is presented to the pilot in the simulator. The position and velocity of the camera and its attitude with respect to the scale model are controlled by outputs from a computer programmed to solve the aircraft equations of motion. While this approach has been successfully employed in numerous simulators, it does suffer from several technical limitations, including depth of focus, field of view, and signal-to-noise ratio (S/N) obtainable. Other limitations may occur because of the physical size and inertia of the optical sensors and the TV cameras.

From a practical standpoint, any model that contains objects and textural features that do not move with respect to the model and do not change size and shape can be constructed. The most serious problems of static environment modeling result from the dynamic range to be covered by the simulation tasks. The physical size of the actual model may become prohibitively large if the simulation tasks must include flights of long duration covering large land areas. The range of altitudes to be simulated may require the use of several models of different scale factors in order to provide a visibility range suitable for the altitude being simulated. Other problem areas arise when such environment variables as shadows, reflections, and color variations are to be simulated. These environmental characteristics are usually created by painting the model or varying its illumination.

The model concept, however, provides an appropriate image source for simulation of discrete objects such as aircraft, providing both realistic perspective and optimum fidelity. Although realism from a model standpoint can be achieved at scales of 87:1 (as in H. O. trains), it has been proven that larger scales such as 20:1 provide greater flexibility of simulation since larger-scale models permit the introduction of attitude effects (about one or two axis) within the model with the remaining attitude effects introduced by the model support structure. Increased model size also simplifies the optical pickup design. A typical example of this type of model approach is the Agena vehicle used by Link in the Edwards Space Flight Simulator for image generation for rendezvous and docking. Such a model would be appropriate for generation of the lead aircraft image in formation flight training.

The image pickup associated with any model system has, with few exceptions, consisted of an optical probe and a television camera. Pure optical image relay systems have, to date, generally proved impractical owing to size and weight constraints.

The optical probe design for use with a terrain model system is determined by the minimum separation of model and image pickup, which in many cases is actual contact. For this and other reasons to be discussed, the optical pickup lens design requires an entrance pupil or "look point" outside the optics barrel. In many instances, systems requirements dictate that pitch, heading, and roll effects be incorporated into the lens structure. The pitch and heading functions are normally added at the entrance pupil point of the optical probe by means of a mirror or prism which adds to the complexity of the optical design problem. The prism or mirror physical size and the associated model scale factor determine the minimum separation of pickup and model, and therefore, the minimum real world separation that can be simulated. A typical optical probe assembly with external entrance pupil used is shown schematically in Figure 40.

In addition to the limitation on minimum model pickup separation, limits in pitch angle are also imposed by the physical size and basic geometric requirements of the mirror or prism.

Other factors such as resolution, depth of focus, and adequate light level also enter into the optical probe design. The resolution requirements of a typical optical probe to be used with a television camera covering a reasonable field of view (approximately 50 degrees) are indicated in Figure 41, which provides a resolution plot for the lens of the optical probe. In can be shown that for this application, the depth of field is a function of the diameter of the entrance pupil only and is independent of focal length and relative aperture. The necessary image brightness and field coverage, and resolution (diffraction limit) usually determines the diameter of the entrance pupil and therefore the attainable depth of field. The limitation of depth of focus, therefore, also adds constraints on the model and probe. A typical depth of focus plot is provided in Figure 42.

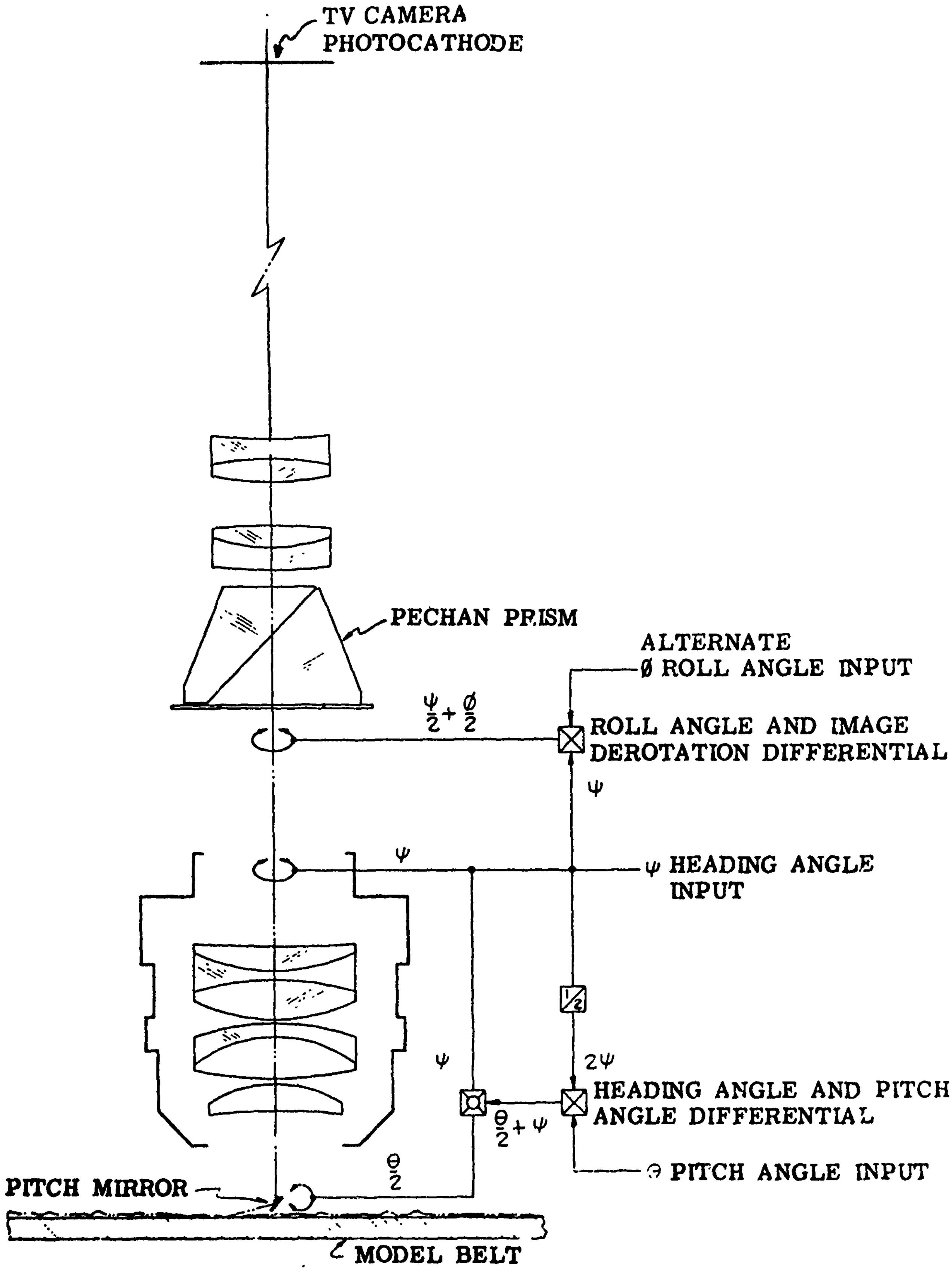


Figure 40 TYPICAL OPTICAL PROBE ASSEMBLY

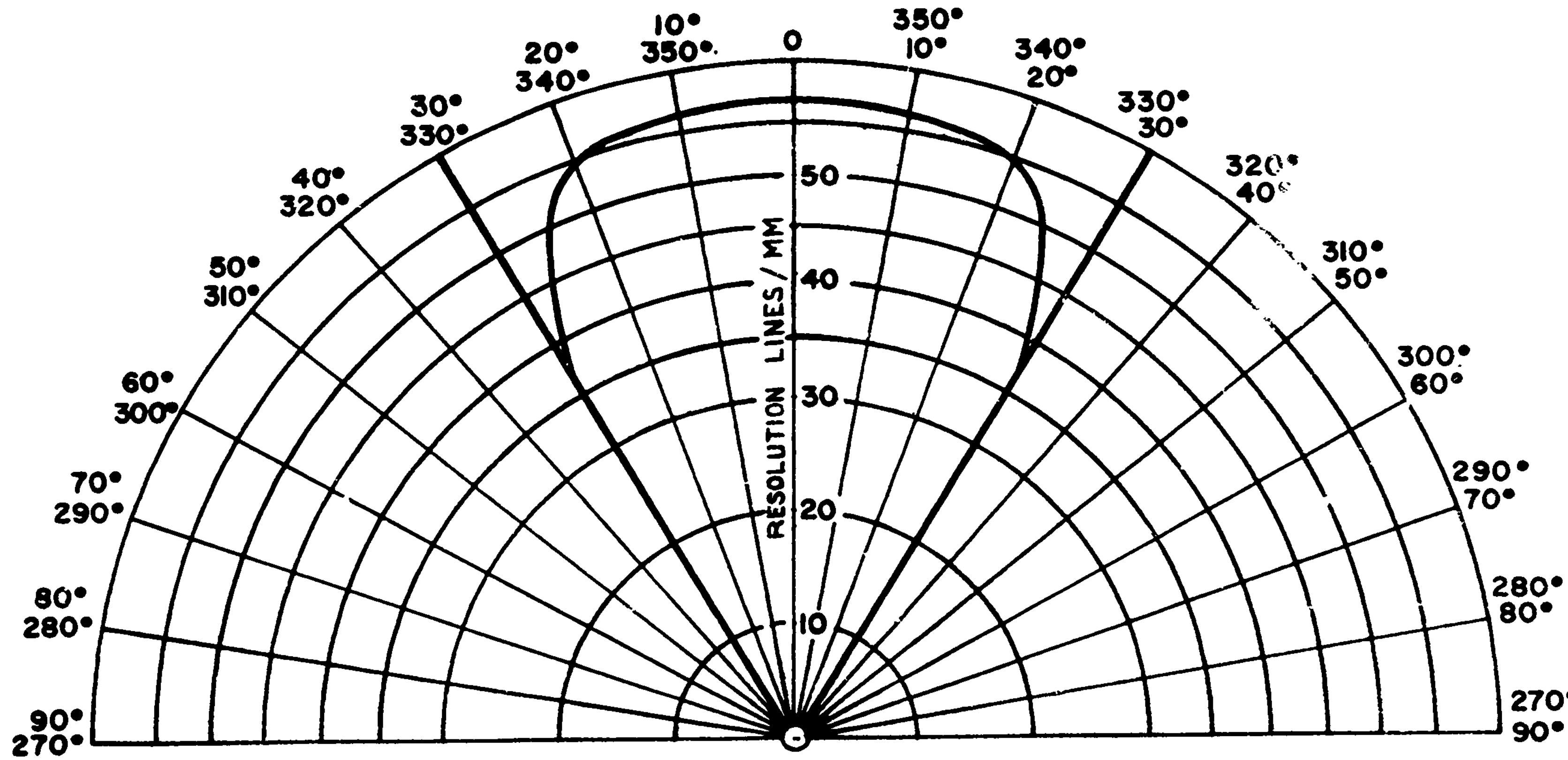


Figure 41 RESOLUTION ENVELOPE FOR TYPICAL OPTICS ASSEMBLY

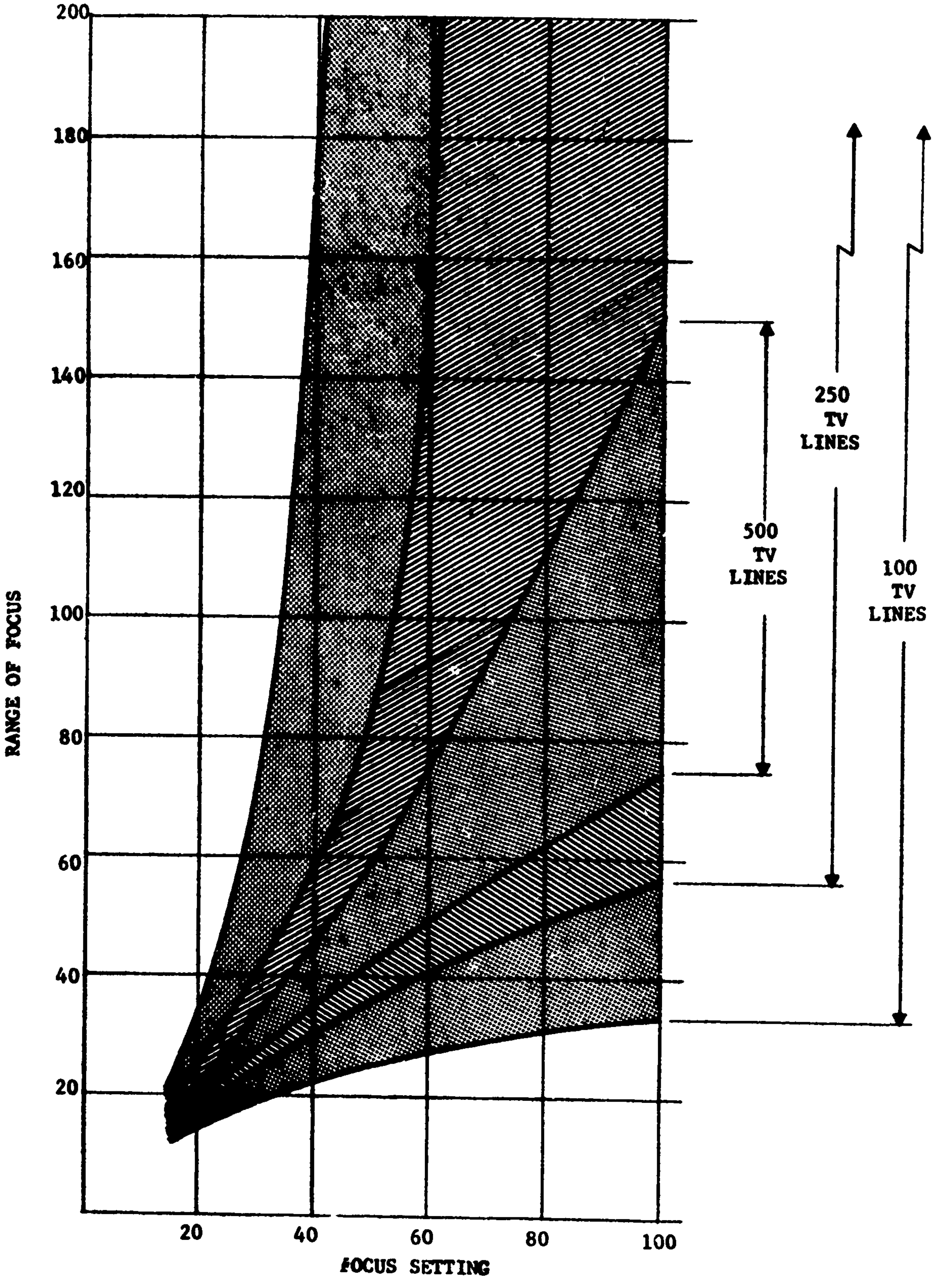


Figure 42 DEPTH OF FIELD VERSUS FOCUS SETTING IN MM

The depth of focus constraints indicated above cannot be eliminated. However, by satisfying the Scheimpflug condition a given plane can be kept in focus. The Scheimpflug condition, simply stated, requires that the object, lens, and image plane must all intersect at a common point for optimum focus conditions. In actual practice, this is accomplished by introducing the Scheimpflug correction of an intermediate image plane.

The Scheimpflug correction requires dynamic controls of lens tilt as a function of probe and model position. Depth of focus problems persist as a function of vertical relief, as indicated in Figure 43.

The television camera associated with any model image pickup system must also be compatible with the model and lens design. The present state of the art in closed-circuit television permits only 1000-line resolution for a monochrome system operating at a standard 30 frames/second flicker-free rate. A color system provides only 500-600 line optimum resolution.

Television resolution normally stated in lines per picture height is actually equivalent to (TV lines/2) optical lines (or line pairs) resolution. The significance of television resolution is not always apparent since it is normally related only to the typical presentation that is seen on a home television receiver. The criterion for determining home viewing resolution requirements was established by assuming the viewer would always be four times the picture diameter removed from the screen. This criterion establishes the viewing angle as 14 degrees, with a resulting resolution of 4 minutes of arc for a 400-line resolution display.

The situation in a visual system normally dictates a field of view in excess of 40 degrees. Assuming a 60-degree field of view, the resolution for a standard 500-line television system would be 14 minutes of arc, and that for a 1000-line system 7 minutes of arc. This clearly indicates that the resolution of television systems is one of the major limitations in the world of visual systems.

Wide-angle optical pickup systems are available exceeding 180 degrees in field of view, but can only be utilized efficiently if the field of view can be broken into separate television channels and recombined at the display by multiprojector techniques. In addition, wide-angle pickup probes usually suffer from some forms of optical aberration which must be electronically corrected at the pickup camera or at the display projector.

Recently, stimulated more by the desire for wide-angle display than by the need for picture quality, this system approach has been implemented using a wide-angle or "fisheye" lens. In this approach, the lens picks up a solid angle greater than 180 degrees with its axis positioned at nadir. Figure 44 shows the relationship between the lens and the model, which are relatively positioned in the three translational degrees of freedom, while

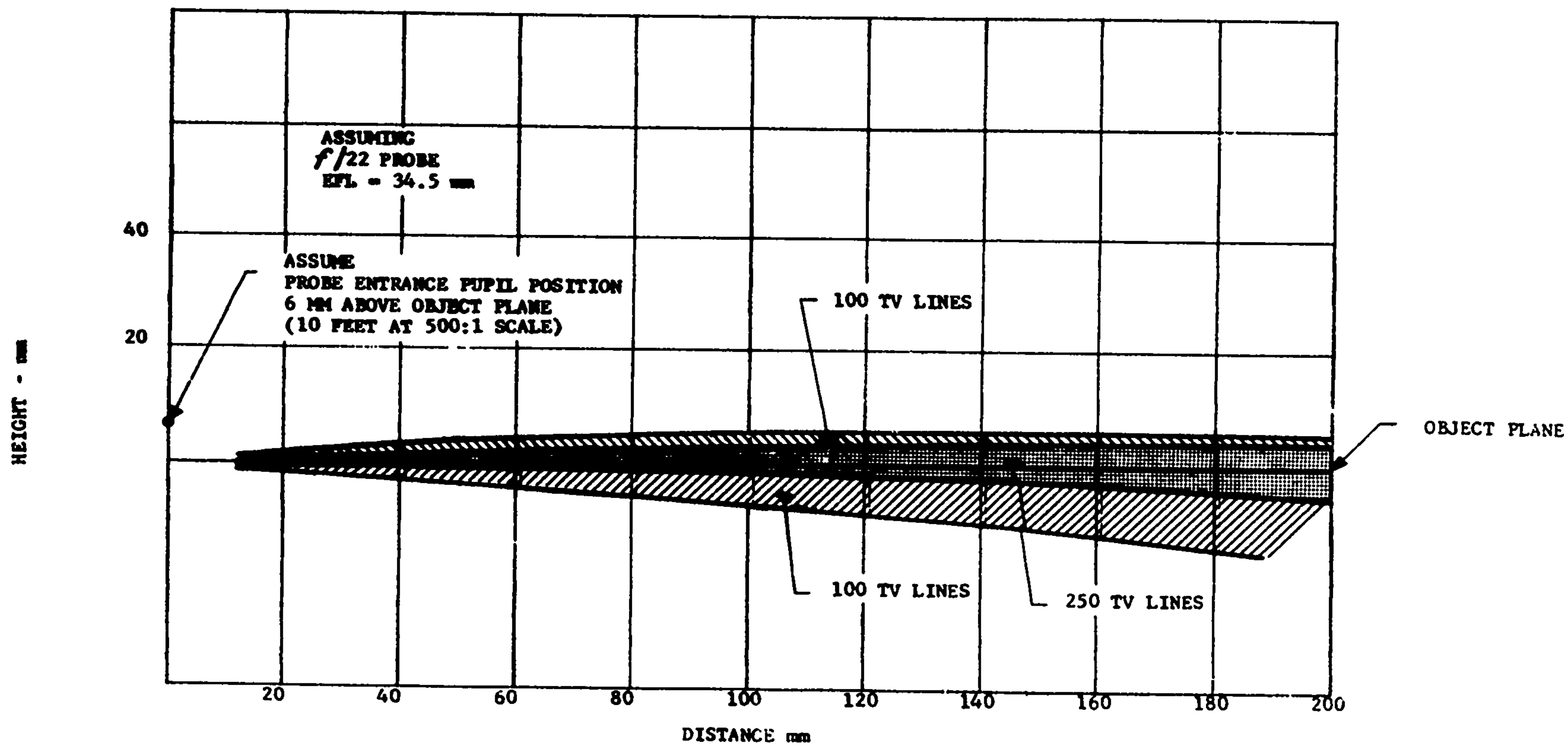
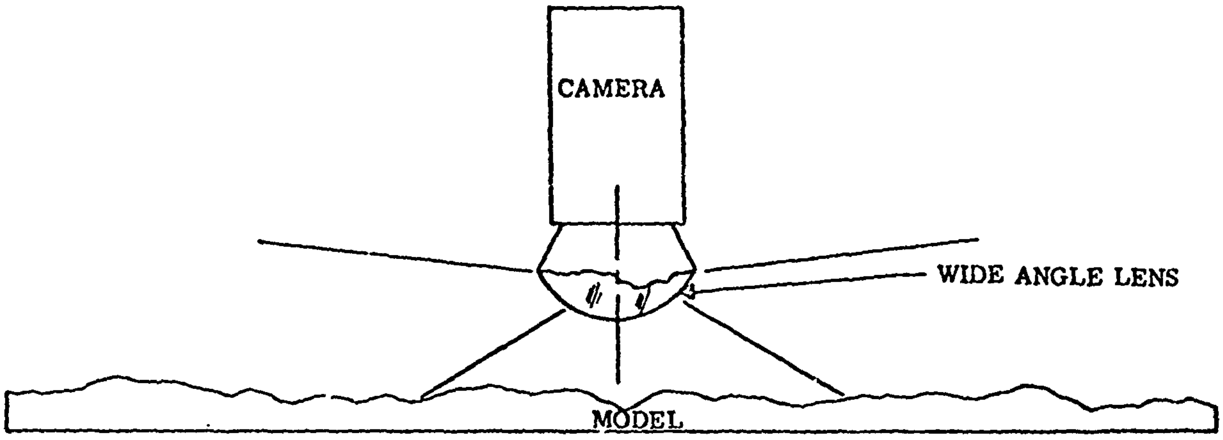
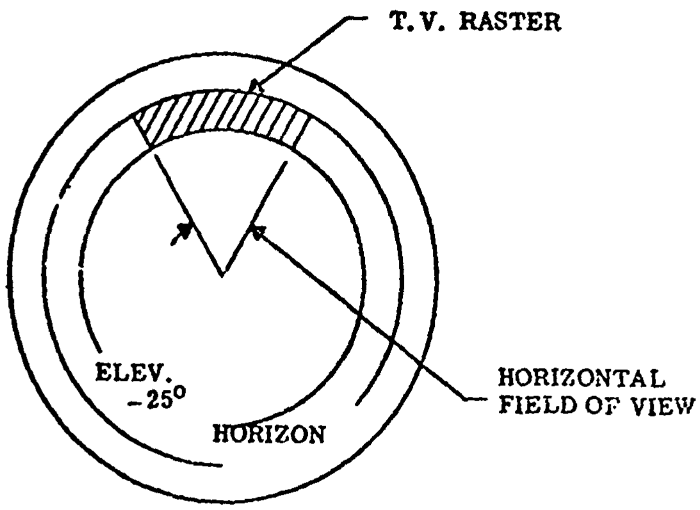


Figure 43 DEPTH OF FOCUS SCHEIMPFLUG CORRECTED PROBE



a) CAMERA-MODEL RELATIONSHIP



b) IMAGE FORMAT

Figure 44 WIDE-ANGLE TV PICKUP

attitude effects are provided by electronic manipulation of the raster shape and position. This full solid angle is reduced to the plane of the camera tube with the inherent high level of distortion that is prevalent in all wide angle lenses. Although this distortion can theoretically be removed from the final display by electronic raster shaping on the camera tube, probably the most critical problem determining final image quality is in the resolution capability of the lens itself. It is apparent from the geometry of Figure 44(b) that the area of best lens resolution, which is the portion along the lens axis, is never used in a display except in the seldom used condition of a 90 degrees downward pitch attitude. The area of principal interest, unfortunately, is the portion of the lens in the extremes of its angular field where the resolution is poorest. Typically, the performance of a lens of this type results in an angular system resolution at the best point in the field of about 15 minutes, if problems of depth of focus can be completely ignored. Although the depth of focus problem associated with this type of lens is not as severe because of the smaller pupil size, some degradation for close viewing should be expected.

In the model systems discussed, and in subsequent systems, the image was generated in the form of a television signal suitable for display via cathode-ray tubes or similar devices. Since the final result of any visual display lies in the image as seen by the viewer, the characteristics of the display device form an integral part of the visual system performance and therefore warrant consideration at this point.

The standard CRT is familiar to everyone by virtue of its use in television, and is quite suitable for direct viewing systems. However, in the application of television to visual simulation systems, they are generally inadequate because of their low light level when enlarged sufficiently to cover the required field of view. Special development in special projection CRT designs has improved brightness levels from about 20 foot-lamberts to 600 foot-lamberts for CRT's up to 21 inches and up to 12,000 foot-lambers on 5-inch projection CRT's (black and white), both with the capability of providing 1000 lines resolution or better. These brightness levels are approximately equivalent if they are projected onto a screen or viewed through magnifying optics on an equal-field-of-view basis. For example, if projected onto a rear-projection screen and viewed through collimating optics over a 60-degree field of view, either CRT would provide a brightness of about 3 to 10 foot-lamberts.

In color TV displays, however, CRT brightness is still limited to about 20-30 foot-lamberts because of their shadow mask construction. Thus, under circumstances similar to those outlined above, the displayed image would have a brightness of only about 0.15 to 0.45 foot-lamberts.

This is generally unacceptable and led to the development of the Eidophor projector of Gretag, Limited, Switzerland, the "light valve" projector of General Electric Company, and the Schmidt projector, typified by the Dalto Electronics Corporation's Amphicon series. The Eidophor Model EP6(300) simultaneous color projector is capable of providing up to about 5 to 15 foot-lamberts under the conditions above; the "light valve" provides about 1 to 3 foot-lamberts, as does the Amphicon "600." With brightness levels of this magnitude, obtaining acceptable image quality with simulated daylight cockpit lighting must be questionable. This is one area which should be studied experimentally since obtaining brighter displays could well lead to costly advancements in the state-of-the-art.

Another parameter which is often limited by the TV display is resolution. If, for the moment, we assume no constraints on resolution due to the storage medium or pickup device, the resolution of the display is governed by spot size, phosphor grain size, and the number of lines in the raster (assuming a raster format is used).

Of the three limiting parameters, the dominant one is the number of raster lines in most applications. Spot size limitation occurs only when the number of raster lines is so great that the spots overlap on successive lines or when using calligraphic displays. Phosphor grain size is even less restrictive because it affects resolution only when the spot size is reduced to a point where the grain size is appreciable by comparison.

A conventional 1023-line raster display actually contains only about 1000 lines with video information because of blanking during vertical retrace. Since TV resolution is defined in terms of black-to-white, or white-to-black transitions which can be achieved during the presentation of one full raster (or frame), the maximum possible resolution is 1000 lines vertically. In actual practice this can be attained only in systems in which the video is generated in synchronism with the line generation because of the random misregistration of the pickup device scan lines with respect to a 1000-line target. This is taken into account in assigning a "Kell factor" to the system. The Kell factor for a good closed-circuit TV system is about 0.7 to 0.8, which means that the 1000-line system can actually resolve only about 70-80% of its theoretical value, or 700-800 lines. This determines vertical resolution.

Since the human eye has equal resolving power in both horizontal and vertical directions, it provides little benefit to increase the horizontal resolution appreciably beyond the vertical since this would result in an unnatural picture; that is, one which is not normally encountered in real life. Some apparent increase in scene resolution can be obtained, however, by providing a horizontal resolution of about 1.2 times the vertical. Thus, a good 1000-line TV display might provide a vertical resolution of 750-850 lines and a horizontal resolution of 900-1000 lines. When used with a visual display

system presenting a 60 x 60-degree field of view, the angle subtended by resolution elements is 4.8 minutes vertically and 4 minutes horizontally.

The horizontal resolution of the TV display is determined primarily by the bandwidth of the video amplifier chain. In the example of the 1000-line black and white display, in order to provide the 900-line horizontal resolution it is necessary to supply at least 450 black-white-black cycles of video information during the active horizontal trace time of about 23 microseconds (allowing 9.6 microseconds for horizontal blanking), which is 20 mhz. This is not at all unreasonable with today's components and technology. Providing a wider bandpass than required generally results only in a reduction of S/N.

Currently, efforts are underway within various companies to develop 2000-line (or better) TV systems, but so far none have been successfully produced. As far as displays are concerned, the problem lies in the high sweep rates required. In pickup devices the problem is primarily one of spot size and deflection control.

Of the three color projection devices discussed, only the Eidophor, with 945 lines, goes beyond the standard commercial 525 lines per frame, although the technology is available to increase all three to 1000-line systems with only moderate development effort. However, until such color projection TV systems have been developed, it appears that any TV display systems which will be used in studying the importance of picture resolution on training efficiency should be black and white, not color. The use of the Eidophor or the light valve projector is also of questionable suitability with a motion system because of the oil films used.

A summary of characteristics of the camera-model systems is included in Figure 54.

9.4.2 Film Projection Systems

The limitation of information storage (scale factor) of a model system can be overcome by substitution of photographic film for the three-dimensional model. Film storage capability can easily provide a 20:1 increase in information storage over the three-dimensional model approach and is capable of superior color rendition and overall quality. Film, however, provides only a two-dimensional representation of a three-dimensional scene.

A two-dimensional representation, however, is quite applicable to distant scenes, such as high altitude or orbital scenes of the earth, as long as the proper correction distortions and attitude effects are applied

prior to viewing. Perspective correction distortions and attitude effects may be introduced in the film readout system optically if standard optical film projection techniques are employed or by raster shaping if electronic film readout techniques are used (see 9.4.3).

Historically, the first approach to using direct film projection for visual simulation is the point-light-source projection of a large transparency film onto a screen in a manner represented in Figure 45a. In this approach, a point source of light is positioned to the scaled analog coordinate of the aircraft, and the necessary keystone distortion for correct perspective viewing is introduced by direct projection on a screen. This approach is limited both by the quality of the transparency and by the physical dimensions of the point source, as illustrated in Figure 45b. This sketch shows how a point source with physical dimensions causes a sharp line in the transparency to be focused over a substantial area on the screen as a result of the physical size of the "point" source itself. It is obvious from the geometry of the display that the farther from the transparency the "point" light source can be located, the more nearly it functions like a true point. Since the separation of the point and the film must be scaled proportionately with the transparency scale, it is apparent that such systems are truly most effective only for relatively high-altitude flight (e.g., for aerobatics and airwork or high-altitude navigation). However, for high-altitude navigation training a large area of ground coverage is required, which demands a large scale factor, say 200,000:1 or more, which in turn restricts the scale altitude to limits low enough to render the resolution unacceptable. Therefore, for the facility, the point-light-source system might well provide an area for study in other flight phases, but for training it does not seem appropriate beyond aerobatics and airwork.

Another approach which is capable of freedom of motion within a more limited corridor is available which does provide good resolution, color, and high brightness levels. This is represented by the Vamp* (variable anamorphic motion picture) system designed by Link. It is primarily intended for use as a visual display for takeoff and landing training, and utilizes an actual motion picture of an aircraft approach and landing and takeoff as information storage. This picture combined with servo-controlled distortion optics, presents a visual scene which can be altered sufficiently to provide realistic simulation of displacements from the ideal approach in true perspective. The range of maneuverability is determined by the area of imagery contained on the film and is a function, primarily, of the altitude of the simulated flight. This type of visual display provides, obviously, the most realistic image content of all displays since it uses the real world as its model.

Considering the circling approach to landing as it is taught in undergraduate pilot training schools, the maneuvering limitations of the motion picture projection system might prove too restrictive for general training, but it can provide the best source of highest quality visual display to be used as a standard for color, resolution, and realism in the study programs to be conducted.

* Trademark, General Precision Systems Inc.

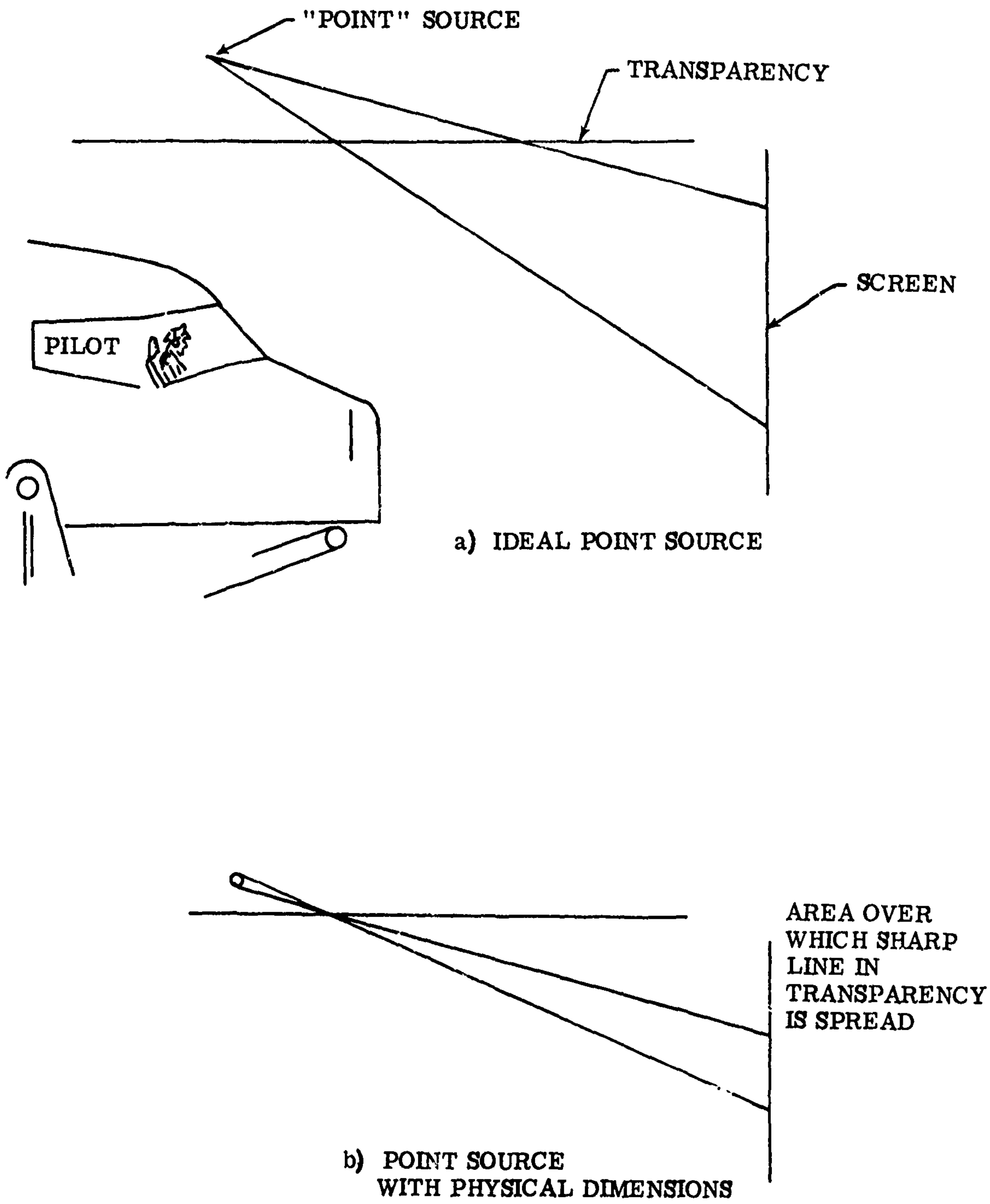


Figure 45 POINT SOURCE SYSTEM

The listings in Figure 54 include the characteristics of the film projection systems.

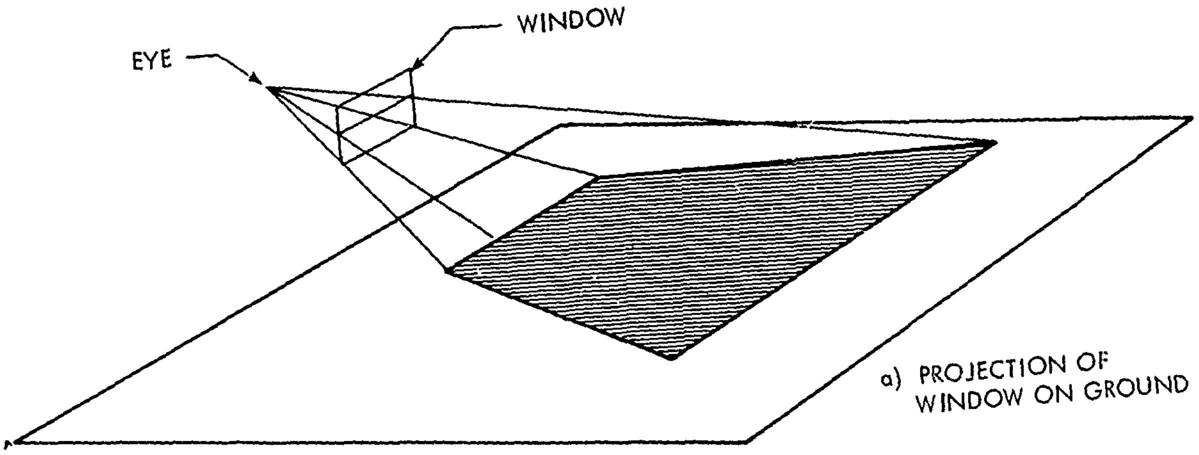
A third method of film projection has been used which involves the optical projection of the imagery contained on a strip film as opposed to the transparency used in the point light source or the frame sequential motion picture projection systems. A strip film projection system was utilized in the Apollo Mission Simulator and the Lunar Module Simulator to present orbital views of the earth or moon suitable for navigation purposes. This system was designed and produced by the Farrand Optical Company of New York. Although it is theoretically possible to extend this concept to provide lower level visual scenes, no such system has been developed yet so far as could be determined from the vendor survey made. However, such a system, if available, could be used for navigation training to the same extent as the two-dimensional transparency reconstruction system described in 9.4.3, while providing more realism in detail, color, and possibly resolution. The ground area coverage in this case, however, would be necessarily restricted to a relatively long and narrow corridor since wide excursions would not be achievable on 5- or 9-inch film at the scale factors which would be used. For example, at a nominal 200,000:1 scale, the useful width of 5-inch film represents about 12-1/2 miles and 9-inch film about 24 miles. The corridor, of course, may be as long as desired.

9.4.3 Transparency Reconstruction

In order to make use of the information storage capability of a film transparency, electronic scanning rather than optical projection can be utilized. In this approach, a constant high-intensity beam of electrons is swept, in time, across the low-persistence screen of a flying spot scanner in a specified raster pattern. The raster is focused on the transparency, which modulates in intensity the light flux passing through it. This time-varying flux is detected by light-sensitive photomultipliers which in turn generate voltages proportional to the incident light flux.

The transparency utilizes a photographic emulsion for storage and contains the area over which the aircraft is to be flown as a vertical photograph taken from "infinity." One approach to image generation from this type of storage is the use of a flying spot scanner with keystone distortion introduced into the raster so that the resultant display shows the correct perspective of a flat earth. In other words, the shape of the raster on the flying spot scanner is equivalent to a projection of a rectangular windshield (display) onto the ground from the aircraft position as shown in Figure 46.

A combination of the three-dimensional qualities of the model system and the information storage capability of film is combined in the Link-developed two-transparency terrain reconstruction system. Basically, this system generates its visual information by simultaneously scanning a



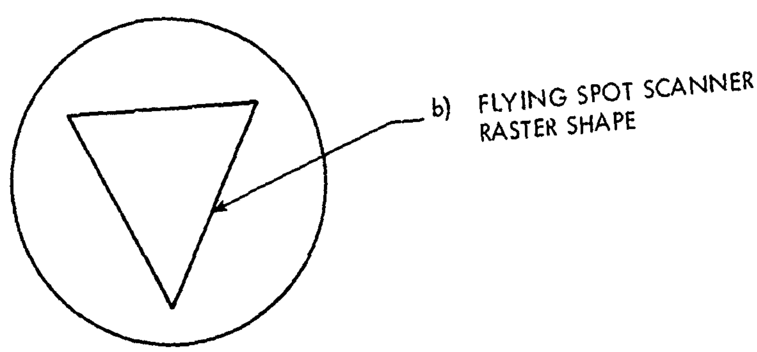


Figure 46 TRANSPARENCY SCANNING RASTER

vertical photographic image of the ground plane and a transmission-encoded elevation plate. The scanning raster on the film plates is the result of a point-by-point mapping of the display window onto the ground plane. A combination of the point-by-point shape of this scan raster and the motion of the film plates below the scanner generates a simulation of the visual scene. In exact synchronism with the transparency scan system, a high-brightness projector "paints" the visual scene onto the display window. Figure 47 illustrates the general principles involved with a block diagram.

The implementation of the requisite mapping functions causes the flat earth terrain map to be imaged in correct perspective onto the display window. The FSS system scans out on a line-by-line basis to the limits of its scan format, at which point an earth-sky boundary is simulated. The second video channel — i.e., the elevation channel — is required to simulate the appearance of correct elevation contours. This simulation is accomplished by a perturbation of the vertical location of viewed objects in the display window. As the system traces out a pattern of vertical lines in the display window, the flying spot is forced, at each instant, to the correct point on the terrain transparency, which represents the ground plane. Simultaneously, each point's elevation is measured by transmission of light from the "flying spot" through the elevation plate. Each instantaneous elevation value corresponds to a vertical position shift in the display window. This vertical position shift is computed from the elevation signal from the transparency and added to the otherwise linear rectangular sweep pattern used by the projection system.

In order to realistically simulate elevation data, the system must also make sure that all areas of the terrain which are hidden by higher-elevation terrain are blocked from view (occulted) in the visual scene. The scan-transparency system keeps track of this occultation by simply monitoring the progress of the vertical sweep lines on the display. If an elevation perturbation causes the projection spot to double back on itself — i.e., to stop its vertical progress and go lower on the screen — the occultation system senses this and blanks all video until the spot eventually exceeds its last highest position.

The transparency system offers particular advantages over the model system which should be considered. The depth of focus problems discussed in the section on model pickups is eliminated since the all-optical imaging is done from the plane of the flying spot scanner to the plane of the transparencies. No mechanical motion is required to vary aircraft altitude since pressure altitude is a voltage input to the computation. The addition of visibility effects can be realistically and accurately achieved since the displayed scene content is determined on a point-by-point basis.

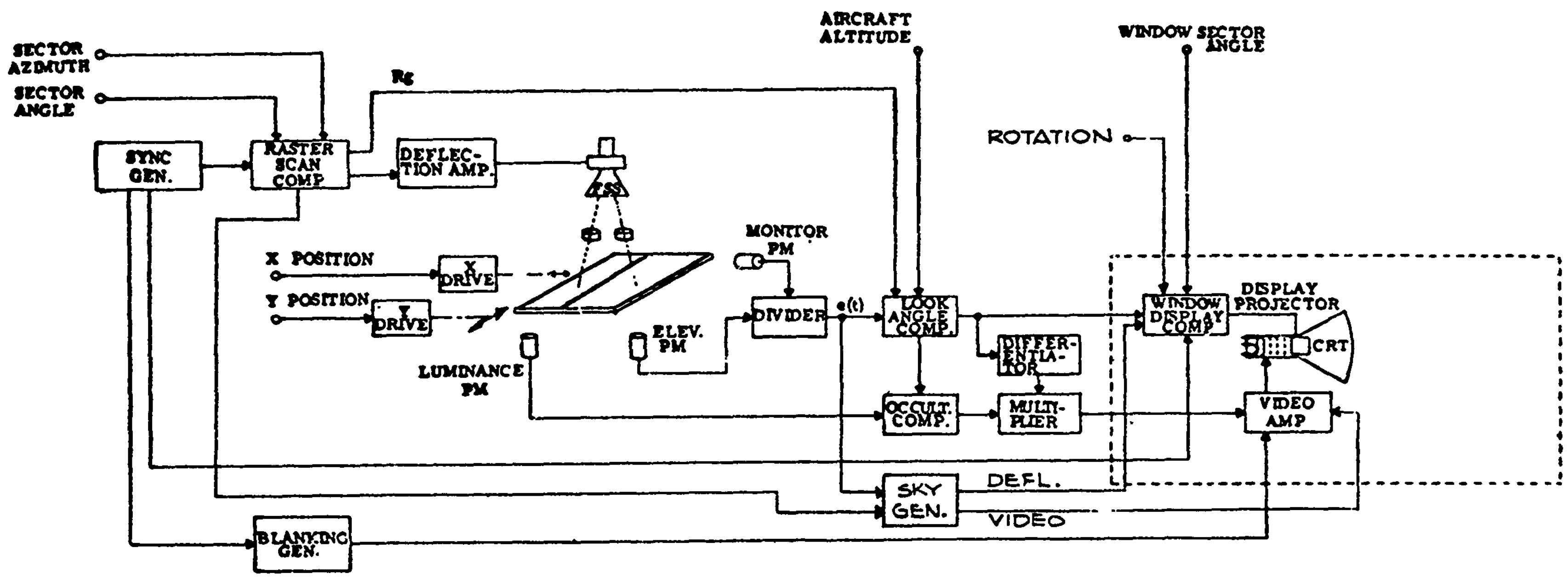


Figure 47 LOW-LEVEL IMAGE GENERATOR - BLOCK DIAGRAM

The image generator readout capability is a function of several variables and must be evaluated based on the particular visual system requirements. The primary considerations of the image generator are the following:

1) Landmass coverage requirement

2) Transparency scale factor and quality

3) Maximum instantaneous range to be displayed

4) Flying spot scanner spot size

Approximate relationships of these parameters are indicated in Figure 48.

The curves indicate limits and relationships between visual range, magnification, scale factor, and transparency resolution. The transparency reconstruction system's basic approach precludes the display of vertical surfaces as contained in cultural detail (such as buildings). Existing systems are monochrone, but can readily be adapted to color if adequate color luminance transparencies are developed. A color system utilizing a limited-area transparency for takeoff and landing training has been developed by Dalto Electronics Corporation, Norwood, New Jersey.

A summary of the characteristics of transparency reconstruction systems is shown in Figure 54.

9.4.4 Electronic Image Generation

The generation of visual imagery by digital computer systems involves storing the data describing the visual environment in computer memory, and solving, in real time, the mapping transformation function which defines the environment onto the display or image plane. Thus, a description of the visual environment exists only in the form of numerical data, and a physical scale model and its associated optical probe, sensors, and servos are eliminated.

A number of attempts have been made to store visual information as electronic data, including both real-world and symbolic imagery. Systems that attempt to store data based on real-world information, however, are faced with memory capacity and data processing rates which greatly exceed the present capabilities of computer systems. Although this limitation may be overcome in the foreseeable future, considering the present rate of advancement in digital computer components and technology, real-world data storage is not considered feasible at this time.

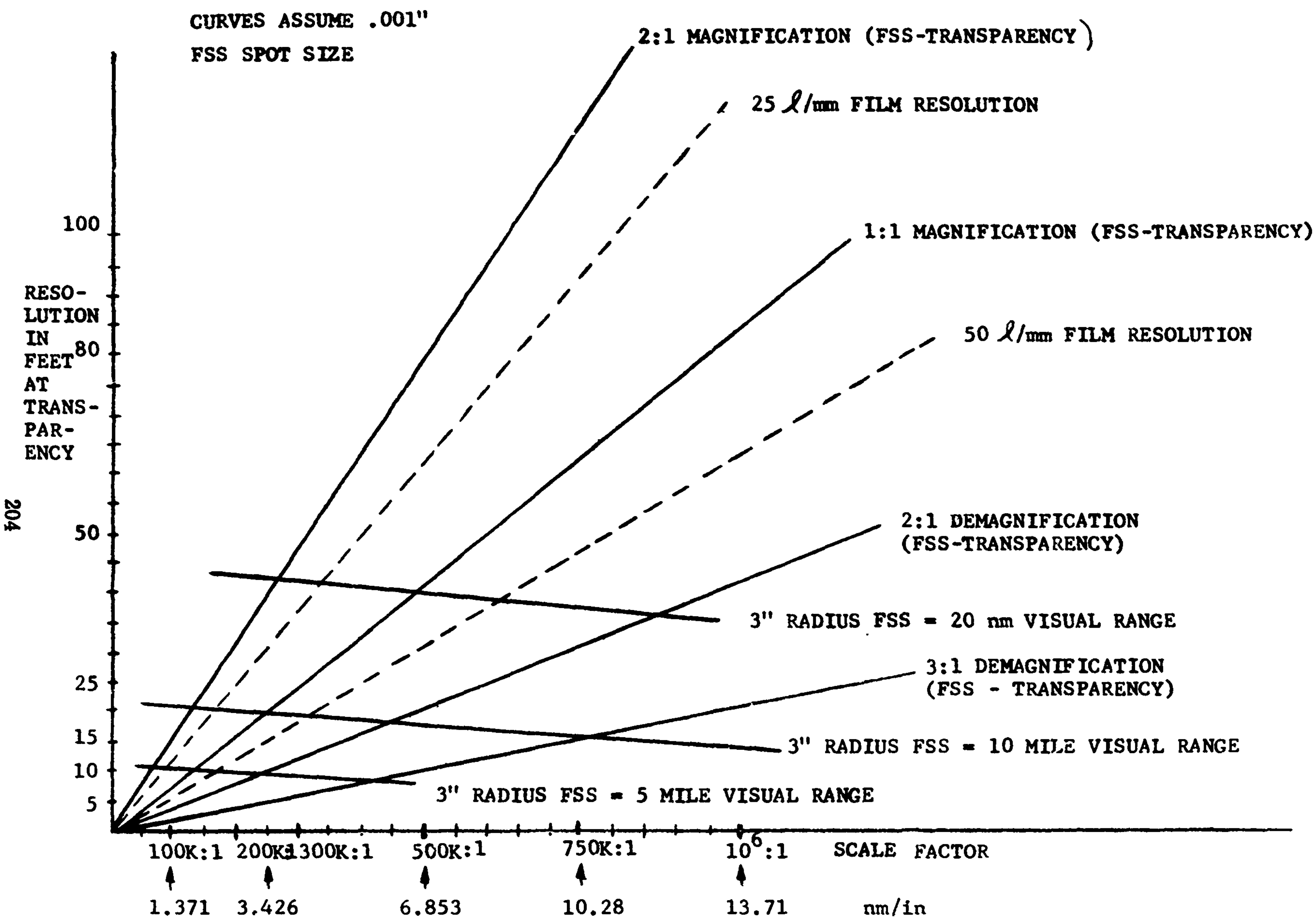


Figure 48 TRANSPARENCY SYSTEM PARAMETER RELATIONSHIPS

More practical systems have been built using electronic data storage in which a symbolic representation of the visual scene is given to the pilot. In these cases, simple geometric shapes are utilized to represent the more complex real world objects, and range in complexity from the simple dot pattern runway and approach outlined in Figure 49, through the three-dimensional solid object pattern shown in Figure 50, to the most sophisticated symbolic image represented in Figure 51. As might be anticipated, the hardware complexity and system cost increase with the degree of sophistication. However, so do the versatility, information density, and effectiveness of the system for general application.

Since the display information is generated and processed in the form of electronic signals, as in the case of the model system and the transparency reconstruction system, the only practical display device is a CRT, projection CRT, or light valve. Therefore, all of the display limitations listed for the model and transparency systems also apply here, and the differences lie in the quality and characteristics of the signals generated.

Since the video signals are generated without the use of cameras, flying spot scanners, or similar devices, the signal-to-noise ratio is inherently higher than it could be with scale model or phototransparency systems. This also implies that greater use can be made of today's wideband (30-40 mhz) video amplifiers to obtain better resolution.

The elimination of optical systems in the image generation also permits an essentially infinite depth of field, and no minimum separation limit exists except the mathematical image screen itself.

Another outstanding advantage of computer-generated visual display is the complete absence of mechanical devices in the image generating equipment, which assures complete freedom of maneuverability.

Figure 54 tabulates comparative performance figures for the three electronic visual systems described in the following paragraphs.

9.4.4.1 Two-Dimensional Pattern

The system used to generate the pattern display shown in Figure 49 is by far the least complex approach to electronic image generation because of its two-dimensional nature. By virtue of this simplification, the mapping function equations are quite straightforward and are given by:

$$x = \frac{X\,d}{h \sin\theta + Y \cos\theta}$$

Figure 49 ALL-ELECTRONIC NIGHT LANDING DISPLAY

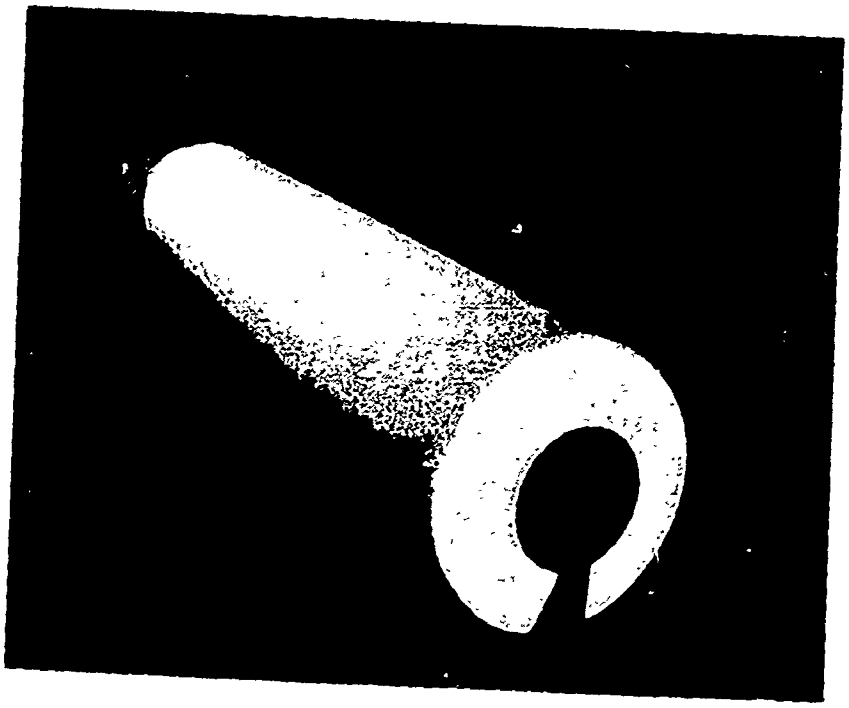


Figure 50 LISSAJOUS PATTERN MODEL

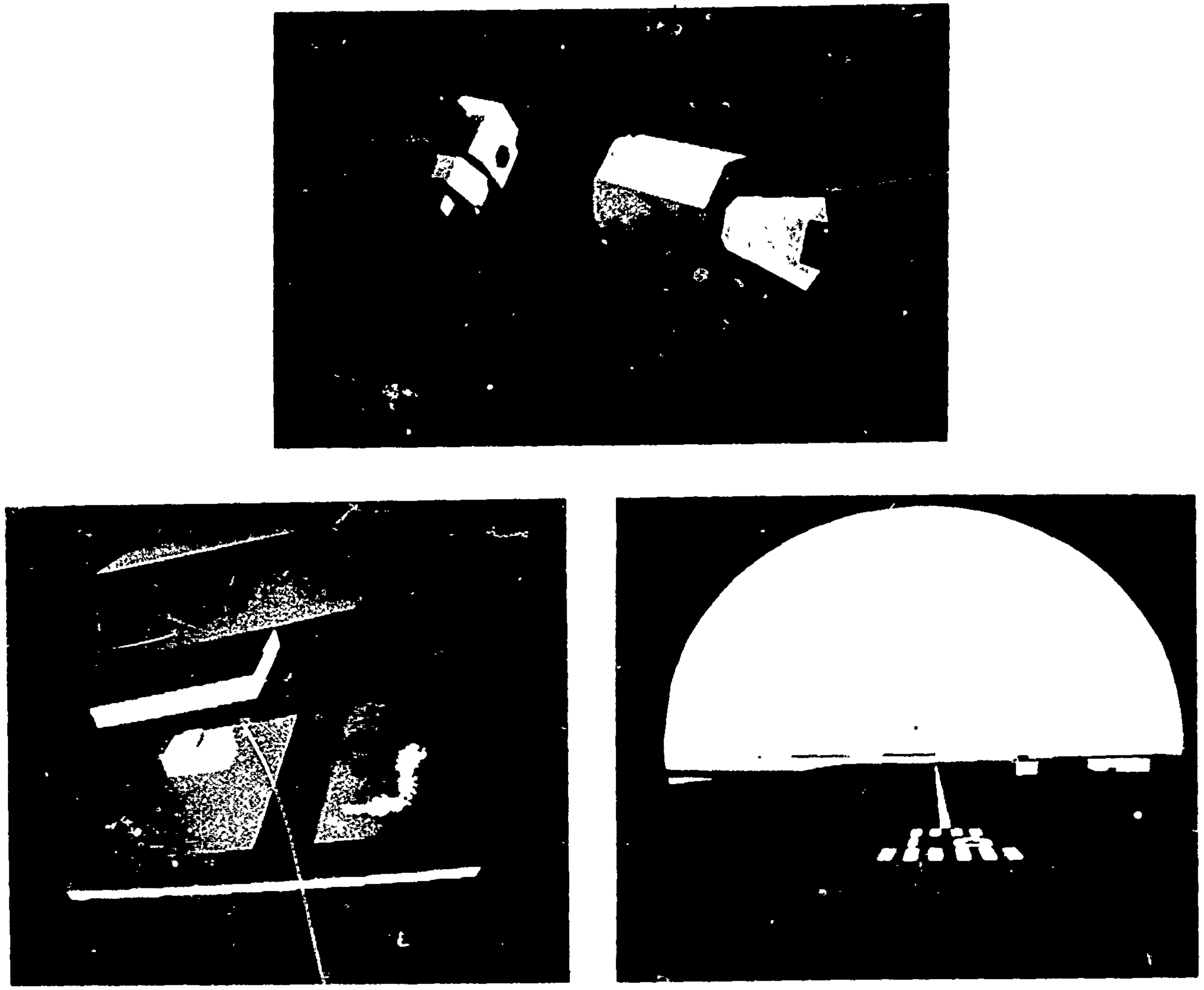


Figure 51 DIGITAL COMPUTER GENERATED IMAGE

$$y = \frac{Y\,d \sin\theta - h \cos\theta}{h \sin\theta + \cos\theta}$$

where: x = display window horizontal distance

y = display window vertical distance

X = transverse ground distance

Y = ground plane range distance measured along the aircrafts heading axis

θ = aircraft pitch

Thus, the complications of eliminating hidden lines and providing vertical relief, both associated with the third dimension, may be neglected. Such a system was built by Link in 1960, is representative of the least sophisticated of all symbolic displays, and is similar to present-day head-up displays in its capabilities for image content.

9.4.4.2 Lissajous Pattern Images

The next more sophisticated system of electronically generating images utilizes Lissajous patterns to form objects. For regularly shaped objects such as cubes, cylinders, cones, etc., the pattern generation is reasonably simple and straightforward. Relative phase relations between the X and Y deflection signals control the aspect from which the object is viewed, size is controlled by signal amplitude, and object shape is determined by wave shaping.

In addition, in order to add the effect of directional lighting and to eliminate lines and surfaces from the opposite side of the object which would otherwise appear, intensity modulation of the signal must be added. This greatly increases the complication of the image generator, but Bell Aerosystems of Buffalo, New York, has successfully demonstrated such displays, and its Agena Electronic Image Generator has been incorporated in the Gemini Mission Simulator at NASA's Manned Spacecraft Center.

The modulation of the signals, being analog in nature, is normally supplied by an analog computer tailored to the particular phase of simulation being undertaken. Since most of the circuits used are of a special nature, the ease of program variation for use in the research facility is subject to some question but probably could be provided when the requirements for test parameter controls are better known.

Application of this approach to general terrain or cultural detail generation has never been attempted, and does not seem directly applicable to simulation of such extended surfaces. Instead it is specifically

intended for generating images of discrete objects such as spacecraft or aircraft. As such it could prove useful in developing the visual cues needed for formation flight training — that is, the lead aircraft and possibly a horizon reference.

9.4.4.3 Digital Computer Image Generator

The most sophisticated and versatile electronic image generation system is typified by the General Electric Company's computer-generated display. This system differs from those described above in that digital rather than analog computation is used, and the image is presented in a conventional raster display format rather than by calligraphic means.

Inputs to the computer are in the form of mathematical definitions of edges which are joined and closed upon themselves to define plane surfaces of bounded extent. These surfaces are then assembled into three-dimensional objects or into extended surfaces. By program control the objects can be made to move independently or be fixed in whichever coordinate frame the programmer chooses. For example, in simulating the visual environment for formation flight, the scene might consist of a terrain background, a portion of the simulated aircraft (such as a wingtip) which is fixed relative to the pilot, and another aircraft which has six degrees of freedom with respect to both the terrain and the pilot.

The image complexity of the currently operating system is limited to a total of 240 edges, but it is quite feasible to expect this capability to be expandable to over 1000 edges within current computer technology, the basic limitation on the number of edges being set by computer processing speed. The present computer uses a 10-megahertz clock rate, but the state of the art is already beyond 20 mhz and is constantly increasing.

The most significant advantage the digitally generated image has over the analog image is its versatility and ease of program variation by conventional programming techniques. An advantage over the model/camera generated image system is the fact that since the video signal elements are computed for each line, the Kell factor mentioned in the discussion of television devices becomes limited only by retrace blanking, thus permitting the maximum possible resolution from a given display format. By increasing clock rates, it is also possible to increase the number of lines in the raster and thereby the resolution.

9.5 DISPLAY SYSTEMS

The final requirement for a visual simulation system requires that the scene be displayed to the viewer. The scene may be symbolic or realistic, color or monochrome, as determined by training requirements. The scene can be readily displayed at the window plane by means of a television tube or rear-projection screen. The positions of objects in the scene, however, would shift in angular position as a function of the trainee's head motion owing to the realitively short viewing distance as compared to the real world. This condition of parallax must be corrected to obtain proper training for such tasks as have been defined as part of the UPT program. Aside from parallax considerations, viewing of an image at close range will result in excessive eye fatigue due to optical accommodation requirements.

The use of any display system, in addition to fulfilling the optical requirements outlined, must also be evaluated from a practical hardware and system integration standpoint. Specifically, the system must be evaluated in regard to its compatibility with the basic training device. Size and weight, for example, are major constraints on the display system if it is to be used with a simulator employing motion cues.

9.5.1 Direct Viewing Displays

Direct viewing of a display screen removed from the window by about 15 feet reduces the parallax considerations for general viewing, and eye accommodation fatigue is essentially eliminated. Parallax for a 15-foot eye-to-screen separation and an allowable head motion of ±6 inches is approximately ±2 degrees.

TV or film projection can be accomplished with front or rear projection screens. Projection screens of either type are capable of providing gain. However, any gain factors are proportionally offset by an increase in the directional characteristics of the screen output.

As the off-axis viewing and/or projection angle is increased, the brightness falloff across the screen increases as a function of the sum of projection and viewing angle and the screen gain. This results in what is commonly referred to as a "hot spot" in the center of the screen. The composite projection and viewing angle can be reduced by increasing the projector throw distance, which, however, dictates an increase in equipment size.

Curved or hemispherically shaped screens offer advantages for wide-angle displays. However, they must of necessity be of the front projection type to be compatible with projection optics.

9.5.2 Infinity-Image Display System

For most aircraft visual simulation systems, a display presented at infinity is desirable. For some specific cases such as formation flight simulation, it is desirable that the lead aircraft be displayed over a range of distance from several miles to a few feet. Two basic types of infinity-image display systems have been utilized in simulators, one using refractive optics and the other reflective optics.

9.5.2.1 Refractive System

A basic infinity-image system utilizing refractive optics consists simply of a single or multi-element collimating lens and a front or rear projection screen placed at the focal length. By the lens formulae, any point displayed on the screen is seen at infinity by an observer. The exit pupil is the lens itself and the maximum attainable field of view is limited by lens aberration to about 60 degrees.

Viewing systems utilizing plastic lenses up to 48 inches in diameter have been designed. Glass elements of smaller diameter, 16 to 30 inches, have been produced in which the glass elements permit correction of aberrations and the use of field compression techniques allowing the maximum attainable field of view to be increased to approximately 75 degrees.

As previously indicated, a refractive infinity-image system may utilize front or rear projection and can accommodate several inputs, some or all of which may be viewed at infinity (see Figure 52).

9.5.2.2 Reflective Systems

A second approach to providing an infinity image display is through the use of reflective optics which is identical in concept to the collimating lens approach described in the previous paragraph. The use of reflecting optics permits displaying larger fields of view (in excess of 100 degrees horitontal and up to 80 degrees vertical) and reducing aberrations. The systems, however, have a low light transmission efficiency.

If an object is placed at the primary focal plane of a spherical mirror, the image of that object will be seen at infinity, as shown in Figure 53a.

In order that the object not be seen along with the image at infinity, an aerial image can be projected into the primary focal plane, as shown in Figures 53b and 53c, by means of a beamsplitter and suitable refractive or reflective optical elements. By further expansion of the concept shown in Figure 53c, optical combination of several images can be achieved. The system depicted in Figure 53d was utilized in the window

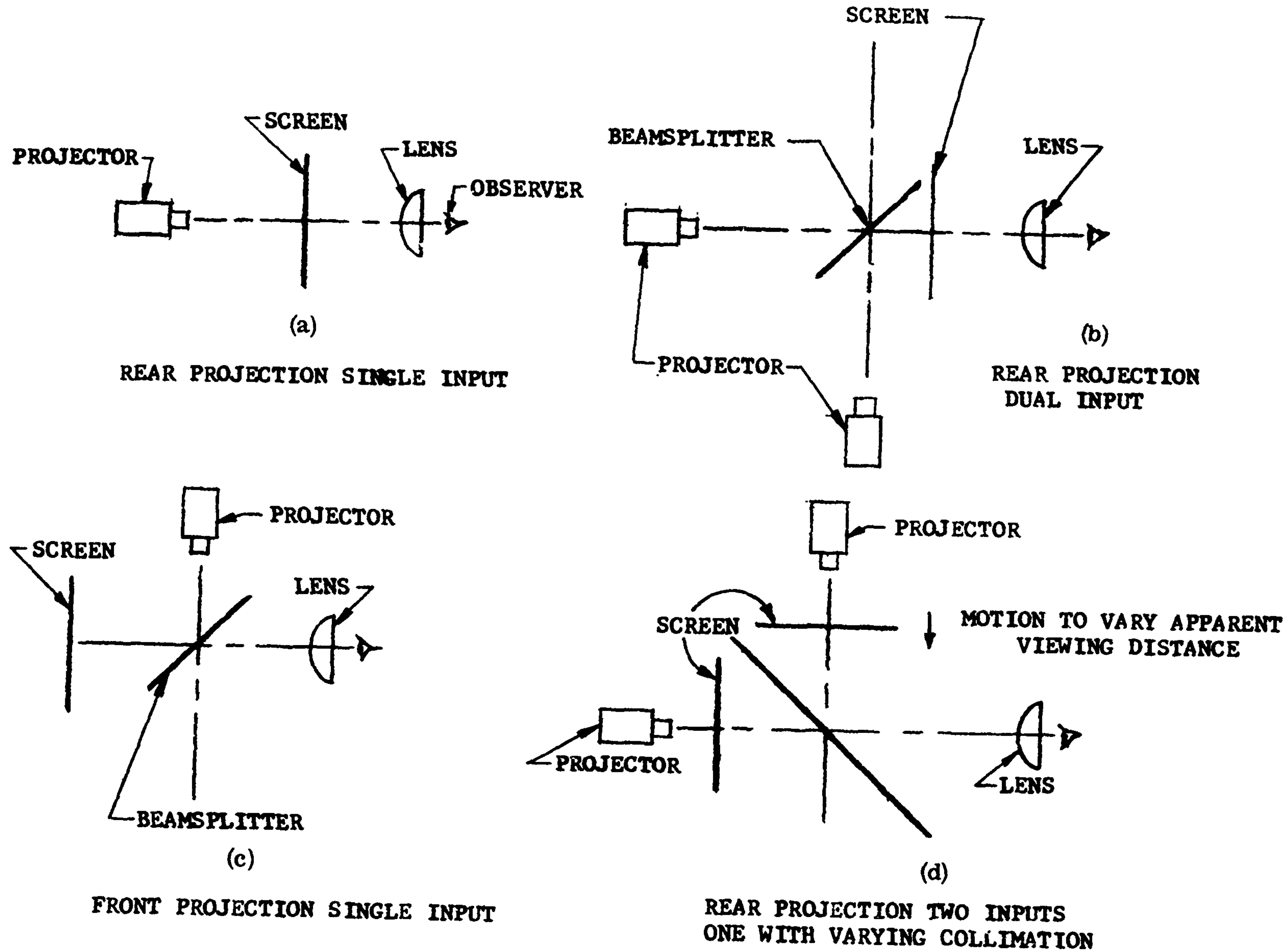


Figure 52 REFRACTIVE INFINITY-IMAGE SYSTEM CONFIGURATIONS

display system of the Link Apollo Mission Simulator to provide:

1) Rendezvous and docking (TV input)

2) Near and distant earth and moon scenes (film projector)

3) Star display (scale model)

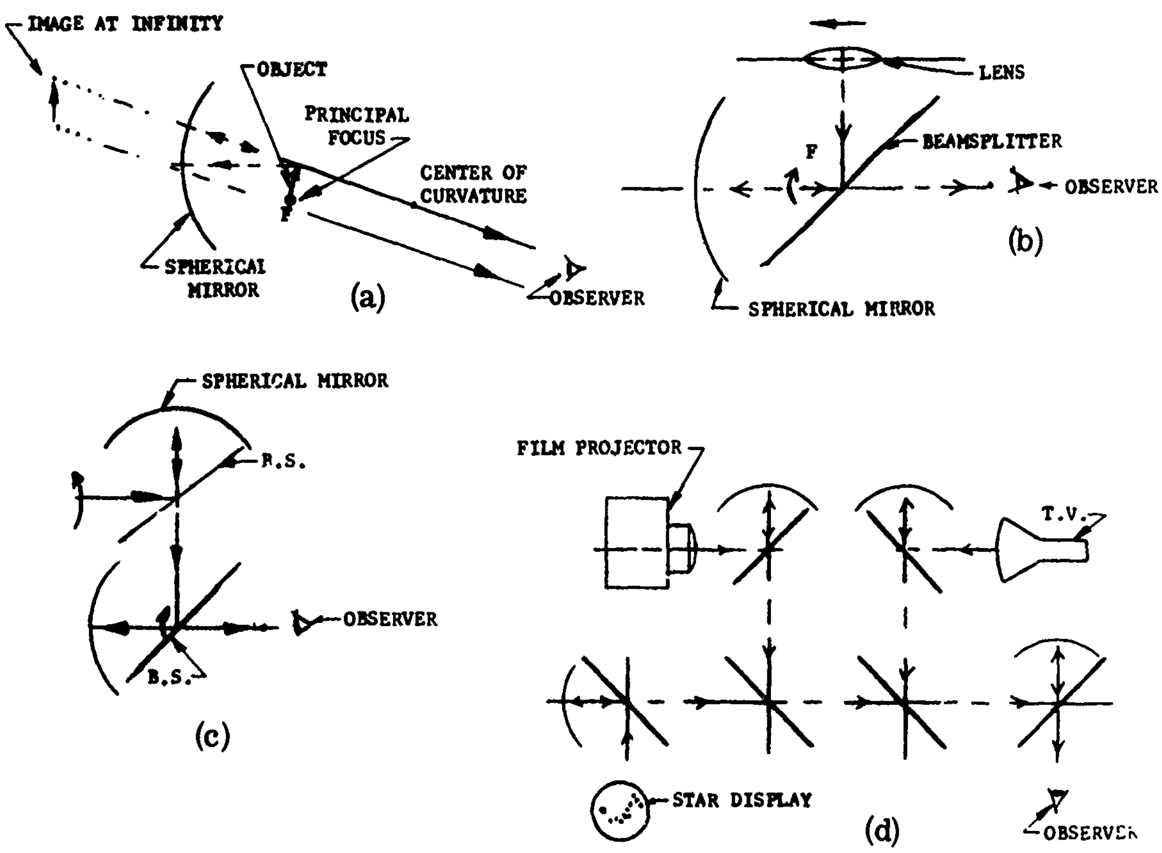


Figure 53 REFLECTIVE INFINITY - IMAGE SYSTEM CONFIGURATIONS

The systems shown in Figure 53, however, are very large and heavy and quite unsuited to mounting on a motion system or of combining in a multiple-display system such as would be required to provide the large fields of view called for in most of the requirements. Recently, some information has been released by Farrand Optical Company concerning a much more compact reflective infinity display system, known as the Pancake Window. Although complete details of its performance are not yet available, it is reportedly capable of providing over 100 degrees of field of view horizontally and vertically, and can be obtained in sizes (and perhaps shapes) suitable for the intended use. Its suggested use as the display optics system on some of the recommended visual configurations is based upon an assumed availability in the proper size and shape to provide the intended display.

9.6 CONCLUSIONS AND RECOMMENDATIONS

From the foregoing discussion of visual system components, systems, and techniques, it is not hard to understand why no visual system to date has achieved the ideal objective of providing a simulator with an external visual environment that is indistinguishable from the real world. Indeed, the qualities demanded of a visual system by the human eye and the human brain are far in excess of state-of-the-art capabilities in visual simulation. The Undergraduate Pilot Training Research Simulation System, however, will prove truly beneficial to both the user and the producer of simulation equipment if it can achieve, in visual systems alone, a better definition of those items which are needed for good training, those which may be used but are not truly necessary, and those items which are superfluous. From efforts such as this, not only will the Air Training Command be in a better position to specify, procure, and evaluate simulation equipment, but from the results of such studies it is possible that better-directed R&D efforts could advance the state-of-the-art one step nearer the ideal of providing a "real world" environment.

Therefore, for the UPTRSS visual simulation requirements, it is the conclusion and the recommendation of this study that the facility make available visual simulation equipment which will cover all phases of flight training and incorporate as many controlled variables for study as possible. In order to accomplish this best, four visual simulation systems of four different types are recommended.

1) Electronically generated image with a wide field of view for maximum parameter versatility and general comparative training studies.

2) Point-light-source projector with wide-angle screen for uninterrupted wide-angle display for training in aerobatics and airwork.

3) Transparency reconstruction system for large land area

coverage and checkpoint image realism for navigation and low-level training.

4) A television display system for formation flight training. Either a model system or computer-generated system would be suitable.

During the course of the study, it has been established that the more advanced phases of training involving formation flying and navigation training are generally accomplished on the T-38 aircraft and/or simulator. Therefore, in the proposed facility it is recommended that the four visual simulation systems be incorporated in four flight simulators, with systems 1) and 2) above used with the T-37 simulators and systems 3) and 4) used with the T-38 simulators. The following sections describe the visual simulation requirements by simulator with some alternate implementations included based upon the values shown in Figure 54.

9.6.1 Visual System No. 1

Since the primary purpose of any simulator is to provide training in aircraft operation without using actual aircraft, it is reasonable to place top priority on that simulator which provides the greatest versatility. It is recommended that Simulator No. 1, therefore, be equipped with a visual system that will provide the greatest degree of versatility for simulation research study in the facility. For this purpose, a digital computer image generator is suggested. The image generated by such a system is defined by a math model, and the type of scene is limited only by the imagination of the program modeler. The quantity of image detail, however, is determined by the hardware capacity available. Thus, it is possible to provide a visual display which is appropriate to any of the training phases listed, with the possible exception of navigation, albeit with a possibly restricted amount of detail.

Since a TV presentation is capable of providing only about a 60-degree field of view with acceptable resolution, and reference to Figure 39 shows a minimum field of view requirement of 120 degrees horizontal by 60 degrees vertical (taxiing), it is anticipated that a multiple display will be required. This could apparently be provided with a dual display. On the other hand, a display field of view of 165 degrees vertical by 240 degrees horizontal would presumably cover any requirement listed. This can be provided by a seven-segment display, arranging the display segments around the cockpit in a pattern similar to the faces of a dodecahedron centered on the center of the cockpit. The actual viewing system can consist of either a set of TV projections on a suitably large (15-foot radius) screen, or possibly by use of the "pancake window" displays of Farrand Optical Company. The latter approach is shown in the facility layout drawing (Figure 56-Part 1) as "Station No. 1". The cockpit chosen is the T-37, since this is the first jet aircraft used by the undergraduate pilots. The General Electric Company's digital electronic image generator is recommended as the image source

since it is the only such equipment discovered during the vendor survey.

The image generator equipment recommended at this time includes one image generator for the central three displays, with a duplicate image processor for four peripheral display segments. This would provide greater detail (capability) in the central viewing area than in the peripheral area, since each processor is limited in the total number of edges which can be provided rather than by the number of CRT displays. If desired, the system capability can be expanded in the future by the addition of image processing capability.

9.6.2 Visual System No. 2

As the pilot in training progresses from the T-37 to the T-38 aircraft, he devotes more time to navigation and formation flight training. Since the first simulator does not contain the capability for navigation flight (visual) training, it is recommended that this capability be the first one added, and that it be on a T-38 simulator.

The earlier discussions have pointed out the reasons for desiring realism in the visual display. From Figure 54 it is fairly evident that the only displays capable of providing both realism and the extended range necessary are the transparency reconstruction system and the hypothesized strip film projection system. For most navigational training, flight occurs above 1000 feet altitude. At these altitudes, presumably a two-dimensional display would be sufficient, but especially so in areas where the terrain is relatively flat. However, for low-level flight training at altitudes down to 100 feet or less, terrain contours become much more evident and exhibit a greater effect on location and identification of targets or landmarks.

Therefore, the visual system recommended for navigation and low-level flight training is given as two alternatives: 1) a three-dimensional scan transparency system, and 2) a strip film optical projection system. The choice between the two lies in the strength of the requirement for presentation of terrain elevation and in mechanization, since the use of multiple CRT displays seems relatively straightforward compared to that of presenting multiple contiguous film projections with maneuvering capability. This simulator is identified on the facility layout drawing as Station No. 2 and the display is shown as a rather nondescript black box projector since the true configuration is not known at this time. No operable system exists at this time and a significant and expensive development will be required.

9.6.3 Visual System No. 3

The third visual display system recommended is once again mounted on a T-37 cockpit. This display is intended for training in aerobatics and airwork and consists of a point-light-source projection of sky and earth,

with a minimum amount of terrain pattern necessary to provide reference points.

Since translation over the ground is incidental to performing the various maneuvers properly, translation of the visual scene is not believed to be an important training cue. Therefore, the projection system envisioned utilizes a spherical transparency with the point light source in the center. Only rotation of the scene about the three axes is required. Such a projector is currently being developed for NASA-Langley by the Northrup Norair Division, Hawthorne, California.

The only vendor of point-light-source systems to respond to the vendor survey was the MGD Research and Development Corporation of Fairlawn, New Jersey, which manufactures the conventional flat plate projectors.

The reason this training capability is recommended as visual system No. 3 is that contact flying, which includes the aerobatics and airwork phases, constitutes the large majority of time spent in the T-37 aircraft, and therefore will supplement the capacity of the No. 1 simulator most efficaciously.

9.6.4 Visual System No. 4

Finally, to round out the visual capability of the facility, a visual system primarily intended for formation flight training is recommended. The capability for such training is contained within the first simulator system, but since most of the formation flying training is actually done with the T-38 aircraft, it is felt that a T-38 simulator with this capability is required.

From Figure 45 it may be seen that there are three possible image generators capable of providing training in formation flying:

1) Scale model — CCTV

2) Lissajous pattern generator

3) Digital image generator

The model system is the only one of the three capable of providing a realistic image of the lead aircraft. Preliminary studies using the No. 1 visual system might be able to provide some guidance on the necessity for realism by using various shapes and images with varying degrees of similarity to the appearance of an aircraft. If realism can be shown to be significant in the training, then the scale model system should be the most desirable.

SYSTEM		FILM PROJECTION			TRANSPARENCY F
PARAMETER	3-D SCALE MODEL - CCTV (1)	POINT LIGHT SOURCE TRANSPARENCY (1)	MOTION PICTURE (1)	STRIP FILM (1)	TWO-DIMENSION [1]
Field of View	H: 50°-60° V: 50°-60° per display	H: 270° V: 180°	H: 40°-50° V: 30°-40° per display	H: 40°-60° V: 30°-50° per display	H: 50°-60° V: 50°-60° per display
Resolution	H: 8-10 minutes[2] V: 10-12 minutes [2]	H: 10-15 arc minutes [2], [3] V: 10-15 arc minutes[2], [3]	H: 3-4 arc minutes V: 3-4 arc minutes	H: 20-220 minutes at 200 ft. alt.[2] 4-6 minutes at 3000 ft. alt.[2] V: 4-60 minutes at 200 ft. alt.[2] 4-6 minutes at 3000 ft. alt.[2]	H: 60-660 minutes at 200 ft. a 12-24 minutes at 3000 ft. a V: 9-180 minutes at 200 ft. a 9-14 minutes at 3000 ft. a
Frightness	B & W: 3-6 f.l. Color: 0.3-0.5	2-3 f.l.[2]	10-20 f.l.	10-20 f.l.	B & W: 3-6 f.l. Color: 0.3-0.5[3]
Contrast	B & W: 30:1 Color: 20:1	B & W: 15:1 Color: 15:1	B & W: 50:1 Color: 50:1	50.1 50:1	B & W: 30:1 Color: 20:1
Image Content	Airport facilities Terrain detail Aircraft-parked or in-flight Cultural detail Visibility to edge of model Special effects[4]	Terrain Horizon reference Cultural patterns	Airport facilities Terrain Aircraft-parked, moving, in-flight Cultural detail CAVU Special effects Day and night lighting	Terrain detail Cultural detail Special effects No vertical relief Visibility to 1C iles	Terrain detail Cultural detail Special effects No vertical relief Visibility up to 10 miles[3]
Performance Range X: Y: Z: ϕ: θ: ψ:	10 miles[5] 5 miles[5] 20-3000 feet[5] Continuous ±35°[6] Continuous	N/A[4] N/A[4] N/A[4] Continuous Continuous Continuous	150 miles[2] Approx. 1.5 x instantaneous altitude 0.55 - 4 times instantaneous altitude ±60° 25°[3] ±20°	12 miles[3] 3000 miles[3] 3000 feet ±60° ±45° Continuous	150 miles[3] 150 miles[3] 200-3,000 feet ±45° ±60° Continuous
Response Angular: Translational:	60 deg./sec. 0-350 knots	60°/sec. N/A	15°/sec. 2/3 to 4/3 x cameral plane speed	90°/sec. 0-700 knots	90°/sec. 0-700 knots
General Comment	1) Typical values listed 2) Values assume 1023 line TV system, object at best focus. See Figure 9 for depth of focus curve. 3) Assumes direct view CRT. 4) Under operator control. 5) Assumes 1500:1 and 20' x 40' model size limitation. Less reduction is possible. 6) With in-flight aircraft model, pitch is continuous.	1) Typical values listed 2) Assuming 500 W lamp, 15 ft. radius screen. 3) Assuming 40,000:1 scale, 1.5 foot diameter spherical transparency. 4) For aerobatic and airwork training, translations would not be implemented.	1) Typical values listed 2) Assumes 15 min. flying time at 600 knots; i.e., approximately 2000 feet of film. 3) Total excursion	1) Theoretical values listed 2) Values given 5° and 30° depression angle. 3) Assumes 200,000:1 film scale; 100 feet long, 5 inches wide.	1) Typical values listed 2) Values given for 5°-30° depression angle 3) Assumes 600,000:1 scale; 18 inches square transpare

A,

	TRANSPARENCY RECONSTRUCTION		ELECTRONIC IMAGE GENERATION		
STRIP FILM (1)	TWO-DIMENSION 1)	THREE-DIMENSION 1)	TWO-DIMENSION 1)	LISSAJOUS 1)	DIGITAL/RASTER 1)
° ° per display	H: 50°-60° V: 50°-60° per display	H: 50°-60° V: 50°-60° per display	H: 50°-60° V: 50°-60° per display	H: 50°-60° V: 50°-60° per display	H: 50°-60° V: 50°-60° per display
0 minutes at 200 ft. alt. 2) minutes at 3000 ft. alt. 2) minutes at 200 ft. alt. 2) minutes at 3000 ft. alt. 2)	H 60-660 minutes at 200 ft. alt. 2) 12-24 minutes at 3000 ft. alt. 2) V: 9-180 minutes at 200 ft. alt. 2) 9-14 minutes at 3000 ft. alt. 2)	H 60-660 minutes at 200 ft alt. 2) 12-24 minutes at 3000 ft. alt. 2) V: 9-180 minutes at 200 ft. alt. 2) 9-14 minutes at 3000 ft. alt. 2)	H 60-660 minutes at 200 ft. alt. 2) 12-24 minutes at 3000 ft. alt. 2) H: 14 minutes V 14 minutes	H 60-660 minutes at 200 ft. alt. 2) 12-24 minutes at 3000 ft. alt. 2) H 8 minutes V· 8 minutes	H 60-660 minutes at 200 ft. alt. 2) 12-24 minutes at 3000 ft. alt. 2) H: 12 minutes V· 12 minutes
	B & W: 3-6 f.l. Color. 0.3-0.5 3)	B & W: 3-6 f.l. Color: 0.3-0.5 3)	B & W· 3-6 f.l. No color	B & W. 3-6 f.l. No color	B & W· 3-6 f.l. Color· 0.3-0.5 3)
	B & W: 30.1 Color: 20 1	B & W: 30:1 Color: 2:1	B & W: 30.1 Color· 2·1	B & W: 30 1 Color 2·1	B & W: 30:1 Color 20 1
detail detail ffects al relief to 10 miles	Terrain detail Cultural detail Special effects No vertical relief Visibility up to 10 miles 3)	Terrain detail Cultural detail Special effects Vertical relief Visibility up to 10 miles 3)	Symbolic image No vertical relief Special effects Visibility to limit of resolution	Symbolic image - Isolated object Vertical relief Special effects Visibility to limit of resolution	Symbolic image Vertical relief Special effects Visibility to limit of resolution
es 3) iles 3) us	150 miles 3) 150 miles 3) 200-3,000 feet ±45° ±60° Continuous	150 miles 3) 150 miles 3) 200-3,000 feet ±45° ±60° Continuous	Unlimited in any degree of freedom	Unlimited in any degree of freedom	Unlimited in any degree of freedom
ec. ots	90°/sec. 0-700 knots	90°/sec. 0-700 knots	Instant Instant	Instant Instant	Instant Instant
etical values listed given 5° and 30° depres- ngle. es 200,000·1 film scale; et long, 5 inches wide.	1) Typical values listed 2) Values given for 5°-30° depression angle 3) Assumes 600,000 1 scale; 18 inches square transparency.	1) Typical values listed 2) Values given for 5°-30° depression angle 3) Assumes 600,000:1 scale, 18 inches square transparency.	1) Typical values listed 2) Probably can be extended to 1000 TV lines horizontal and vertical.	1) Typical values listed 2) Equivalent	1) Typical values listed 2) Probably can be extended to 1000 TV lines horizontal and vertical.

Figure 54 VISUAL SYSTEMS CHARACTERISTICS

B.

On the other hand, if the symbolic image is capable of providing the necessary degree of training, then the digitally computed image generator used with Station No. 1 might be capable of handling the requirement for the extra display, at least on a time-sharing basis. If so, then the necessary displays and video switching circuitry are all that is required to provide the capability.

The third possibility is that the use of a symbolic display is suitable for training, but the computation or image processing capacity is not available from the No. 1 simulator. In that event, it would seem that the use of a Lissajous generator such as that of Bell Aerosystems would provide the most training value for dollar investment.

In any case, the display itself should consist of three CRT's arranged to provide a contiguous field of view of the required size, since each of the three image-generating techniques requires a cathode-ray tube as the final image-forming device. This is shown in the facility layout as Station No. 4.

10. OTHER ENVIRONMENTAL SIMULATION

10.1 AURAL CUE SIMULATION

10.1.1 Requirements

It is apparent that sounds associated with the operation of the aircraft are valuable cues to the pilot indicating performance and status of aircraft operation. These sounds are inherently related to the operations and procedures that take place within the cockpit, and the effects of changes in aircraft configuration.

The sounds typically simulated for a T-26 trainer are:

1) Engine Starter Sound - When either engine starter is on and the ground cart is connected, the engine starter sound generator is excited and simulates both the noise of the air pressure from the ground cart and the increase in sound as the engine fires. When the RPM of the engine becomes greater than 15% the starter sound is replaced by engine noise controlled by engine RPM, and engine noise simulating the low-frequency roar of the engine once it has fired.

2) Random Noise - Random noises are generated and added to the engine noise simulation and to air noise generators

This simple system has proved satisfactory in operation, but it is felt that a more complete and flexible capability should be provided for the UPTRSS, including noises associated with landing gear activation, tire screech on landing, and many other sounds which could be contributing cues. Further, sounds may serve to reinforce information obtained from other sources, or alert the pilot of a system malfunction, and thus sound changes associated with malfunction insertion should be part of the total capability.

A comprehensive study* has been undertaken by Link as part of an in-house R&D program to provide methods of developing realistic sound simulation systems which extend the capabilities of currently utilized systems. This study was concerned with the establishment of the parameters and characteristics of the sounds to be simulated (by analysis of recordings, with frequency analysis equipment) and the techniques to be applied in the generation of the simulated sounds. As a result of this study, solid-state hardware has been developed capable of providing a wide variety of sounds under computer control. The system can be operated either directly from the digital computer or manually. These features would appear desirable for the UPTRSS to permit research in establishing the utility of critical parameters associated with loudness, directivity, frequency content, and parameters associated with system malfunction.

*Link IR&D Project 9061

The following sound simulation capability is recommended for the UPTRSS T-37 and T-38 simulators:

1) Engines (turbojet with afterburner)

2) Engine Starters

   a) Low pressure air compressor (T-38)

   b) Starter-Generator (T-37)

   c) Auxiliary power unit

3) Electrical System

   a) Generators (T-37/T-38)

   b) Inverters (T-37)

4) Fuel System Boost Pumps (T-37/T-38)

5) Hydraulic System

   a) Pumps (T-37/T-38)

   b) Pressure regulator (T-37)

6) Aerodynamics

   a) Aerodynamic hiss

      (1) Airframe

      (2) Landing gear doors

      (3) Flaps

      (4) Speed brakes (T-38)

      (5) Spoilers (T-37)

   b) Air Conditioning, Ventilation, Pressurization

      (1) Air Vent Hiss

      (2) Pressurization noises

(3) Pressure dump noises

(4) Ram Air Turbine (T-38)

7) Other Miscellaneous Noise Sources

a) Vibration due to buffet and rough air

b) Landing gear noises

(1) Doors locking and unlocking

(2) Shock strut extension

c) Touchdown noises

(1) Tire screech

(2) Airframe and landing gear shocks

d) Ground rumble

(1) Engine induced

(2) Airframe rattles due to runway roughness

e) Ground handing equipment

10.1.2 Characteristics

10.1.2.1 Engine Sound Characteristics

Listed below are the requirements for the various types of engine sounds as indicated in the study:

Gas Turbines

Frequency - a function of RPM

Amplitude - a function of RPM and thrust

Components - Turbine whine, compressor whine and jet exhaust

Frequency Range

Turbine - 80 hz to 12, 000 hz

Compressor - 200 hz to 8, 000 hz

Jet Exhaust - Random frequency from 10 hz to 600 hz mixed with white noise

NOTE: The addition of afterburning and water injection to an engine will increase the jet exhaust noise amplitude – no effect on turbine or compressor

10.1.2.2 Fuel System Sounds

Valve sounds are not usually encountered, but they can be evident in jet-powered aircraft. The solenoid valves will produce a metallic "clunk" which is sometimes simulated by gating a band of noise (300 to 3,000 hz) with a square pulse with a width of from 20 milliseconds to 200 milliseconds. A motor-driven valve may produce sounds similar to the electrical system inverters for a short period of time -(1 to 5 seconds).

Pump sounds have the same basic characteristics as elecrical system inverter sounds.

10.1.2.3 Hydraulic System Sounds

Hydraulic pump sounds have the following characteristics:

Frequency Range - 60 to 400 hz

Amplitude varies as system load

Waveform is usually spikes or sawtooth envelope

10.1.2.4 Aerodynamic Sounds

The aerodynamic sounds can be classified as "hiss noises." The majority of these are simulated by using a noise source such as a noise diode, thyratron, or zener diode. The basic broadband noise is "gated" by exponential on-off gates for such things as landing gear doors and bomb bay doors. The airframe air hiss is simulated by controlling the amplitude of the noise as a function of dynamic pressure.

10.1.2.5 Vibration Due to Buffet and Rough Air

Low-frequency sounds are produced by shaking the airframe. These are not frequently simulated. They can be very complex in frequency content.

10.1.2.6 Landing Gear Sounds

Door and shock strut noises are similar to the valve noises in fuel and hydraulic systems, and are gated in the same fashion.

10.1.2.7 Touchdown

There can be two types of sounds associated directly with touchdown. One is the tire screech, the other is the metallic sounds made by the landing gear structure and airframe as the landing shock is absorbed. The tire screech can be simulated by a pulse-gated band of frequencies from 300 to 1,000 hz. The metallic sounds are the same as valve sounds.

10.1.2.8 Ground Rumble

Low-frequency reverberations arise from jet exhausts. This has been simulated by using the lower-frequency components of a noise source and gating these components into the audio system when in proximity to the ground (10-ft altitude or less) with the engine operating.

10.1.2.9 Ground Handling Equipment

Both gas turbine and reciprocating engine units are used. In the case of a gas turbine, the jet engine noise generation techniques can be used. For reciprocating engine driven units a system of three pulse generators ranging from 40 hz to 1,500 hz can be utilized. Each pulse generator would be variable in frequency and amplitude, and these frequencies would then be mixed and inserted into the audio system.

10.2 OLFACTORY SIMULATION

In keeping with the philosophy of providing a comprehensive research and training environment it is recommended that smoke generation equipment be implemented in at least one of the simulators. Smoke filling a cockpit, caused by an electrical fire, can create a severe task loading, and it would seem desirable for research evaluation to provide such a capability. Smoke generation could occur at the insertion of one of several malfunctions by the instructor or researcher. The capability to produce smoke with differing odors appears to be an expensive refinement that would probably not be justified for the UPTRSS.

11. ADVANCED TRAINING CAPABILITIES

11.1 INTRODUCTION

The UPTRSS offers the opportunity to perform research in advanced training systems, specifically in the areas of performance measurement, performance monitoring, and automated instruction. These areas are of extreme importance because the increasing complexity of both the aircraft to be simulated and the digital flight simulator has created a need for more standardized training programs. To provide this advancement in training techniques, objective studies should be performed in order to provide meaningful data in the following areas:

1) Feedback for Training — It has been well established that furnishing trainees with knowledge of the results of their efforts enhances their learning. Feedback is of most value when it is prompt, accurate, and relevant.

2) Trainee Motivation — With the existence of objective standards of performance, not only does each individual have an immediate and concrete goal to strive for, but meaningful and healthy competition between individuals or crews is possible.

3) Prediction of Future Success — Measurement may involve the collection of data from which an estimate can be made (preferably with a specified success probability) of how an individual or team will perform in some future context or universe of events. This prediction of future performance may be an evaluation of aptitude for training or an evaluation which uses measures of training achievement as the basis for prediction of subsequent operational performance.

4) Evaluation of Present Performance — Measurement may involve the collection of data from which the knowledge, skill level, or performance level of an individual or team can be specified. The measures may reflect present performance level in part-task and/or more comprehensive segments.

5) Evaluation of Learning Rate — Measurement data may be collected at several points in a training program in order to indicate the rate at which knowledges and skills are being acquired. Such measures provide a basis for judging an individual's or a crew's present stage of learning and readiness for the next phase in a training program.

6) Identification of Areas of Strength and Deficiency — Measurement data, particularly of a diagnostic nature, may be used to determine in what areas or tasks individual crew members are proficient and in

what areas they are deficient. Such measures pinpoint the need for and nature of further training and suggest how task or environment characteristics may be modified in order to achieve a specified level of proficiency. They can also be used to provide information to the trainee which will speed his learning.

7) Evaluation of Training Effectiveness — Measurement data may be used to determine the nature and extent of changes resulting from a training experience. An important subarea here relates to training research and the evaluation of the differential effectiveness of alternative training methods, the contribution of component proficiencies to overall mission accomplishment, schedules, simulators and simulator features, etc.

8) Selection and Placement — Measurement data may assist in identifying individuals more likely to achieve a given level of proficiency, that is, the identification of persons who either will require less training or will profit the most from a given amount of training.

9) Refinement of Criterion Information — Measurement data may provide the basis for refinement of the criterion by helping to define further what constitutes successful or proficient performance.

10) Definition of Requirements — Measures of performance may permit statements of functional requirements for training equipment to be specified more precisely. Training standards can be made more precise and objective, and training equipment more effective.

11) Evaluation of Equipment and Procedures — This can include determination of whether given items of operational equipment or procedures permit attainment of required standards, as well as determination of the better of two equipments or procedures. For example, total training time to a proficiency criterion can be used as a measure of effectiveness of a specific equipment or procedure. Items that can be evaluated include instruments, control feel, and personal equipment (e.g., seating).

12) Evaluation of Instructor Capability — The best measure of an instructor is the kind of student he turns out. Reliable and valid measures of trainee performance permit instructors to be evaluated directly by their product, rather than indirectly by their knowledge of the subject, teaching manner, etc.

13) Condition or State of the Individual in Relation to the Task — Measures dealing directly with the state of the individual which describe the behaviors and/or results of acts that have occurred.

The advanced training features recommended to be investigated by means of the UPTRSS will provide data in relation to many, if not all, of these parameters. This is a natural consequence of the fact that the various systems developed to support flight training in current simulators have been formulated along these lines.

The training features which may be classed as "advanced training" innovations include:

1) Performance data accrual

2) Performance data analysis

3) Student feedback

4) Adaptive training

5) Instructor displays

6) Automated training system

Some of these features, such as performance data accrual, have reached some form of implementation, while others, such as adaptive training, are clearly defined but not yet implemented. Prior to discussing the immediate and future facility requirements in this area, definitions of each feature are in order.

Data accrual can encompass both processed and raw information. It is possible to design mathematical models which will monitor selected parameters and provide permanent summary data. The RMS deviations from a prescribed altitude during a particular task or the angular rates encountered at the point of entering a turbulent area are typical examples of summary data. An analog recording of selected parameters is another type of performance data; however, it may be unprocessed. Still another form of performance data is printed with respect to a cyclic base line by means of a high-speed printing device.

Performance data analysis consists of real-time or off-line computer programs which condense data into forms needed for trend analysis. The programs may be statistical in nature, but also may be in other forms. Off-line analysis may consist of graphical or printed data demonstrating trends in the selected parameters.

To date student feedback has been limited to quantitative, immediate feedback of performance (via instruments) and to qualitative appraisal by the instructor based on his observations and background. Automated

feedback should provide objective appraisals to student actions. The form it may take varies: some schools of thought suggest audio methods, while others prefer visual techniques.

Adaptive training encompasses the methods and techniques needed to set up an exercise based on student standing in a training program, monitor performance during the exercise, make decisions related to performance, advance to the next prescribed exercise, and provide the necessary data for recordkeeping purposes.

All methods needed to convey relevant performance information to the instructor are considered part of any instructor display system. The instructor area is fully treated in Section 4 of this report.

The concepts leading to automated instructional systems for undergraduate pilot training are composed of the various features previously mentioned. The additional constraint is completely automatic operation, including evaluation, within each task and from task to task.

11.2 PRESENT CAPABILITIES

The presently available advanced training features are limited to data accrual, instructor displays, and simplified adaptive training systems.

Unprocessed aircraft data does not require sophisticated programs to provide output. The data can be output via normal data channels. Analog recorders may also be utilized with minimum programming via normal simulator D/A channels.

Data summarization requires more sophisticated prior analysis and subsequently more programming. An example of this is monitoring phase performance during a normal takeoff. The takeoff roll phase has been described utilizing the following parameters:

1) Number of centerline crossovers

2) Maximum deviation from centerline

3) RMS deviation from centerline

4) Average frequency of nosewheel control movements

5) Maximum roll angle

The program to monitor these parameters and provide a readable printout requires approximately 350 core locations for instructions and

data. Additional requirements would be a RAD storage file and a printer. These requirements are based on actual operating programs prepared for a Boeing 707 commercial flight simulator.

A simplified adaptive training flow diagram, for decision making only, is illustrated in Figure 55. Admittedly, this is a primitive example, however, this is an area where considerable research needs to be done. This technique relies on scoring information developed separately. Additionally, the manner in which the difficulty level of the task is changed is predetermined and is based on average data.

11.3 CAPABILITIES RECOMMENDED FOR FUTURE STUDY

The following advanced training features are recommended for future study:

1) Performance data analysis

2) Student feedback systems

3) Advanced adaptive system

4) Automatic instruction system.

The following sections discuss possibilities in each area.

11.3.1 Performance Data Analysis

There should be provision for two levels of analysis programs: one level to analyze trainee performance data to determine various types of trend information, prediction, scheduling and perform other similar functions; and an additional level to determine whether or not the other level is performing the required function.

The data processing system servicing the problem can be operated in one of two modes. The information may be processed on a real-time basis with several remote consoles at training sites. The second mode of operation would be batch processing. One of the computers servicing the simulators could be used in off hours to service the processing problem.

11.3.2 Student Feedback

Studies in which television is used to provide self-confrontation, to facilitate student performance analysis and measurement, to enhance the usefulness of preflight and postflight briefings, as an augmented study aid, and for a number of classroom applications should be considered as a

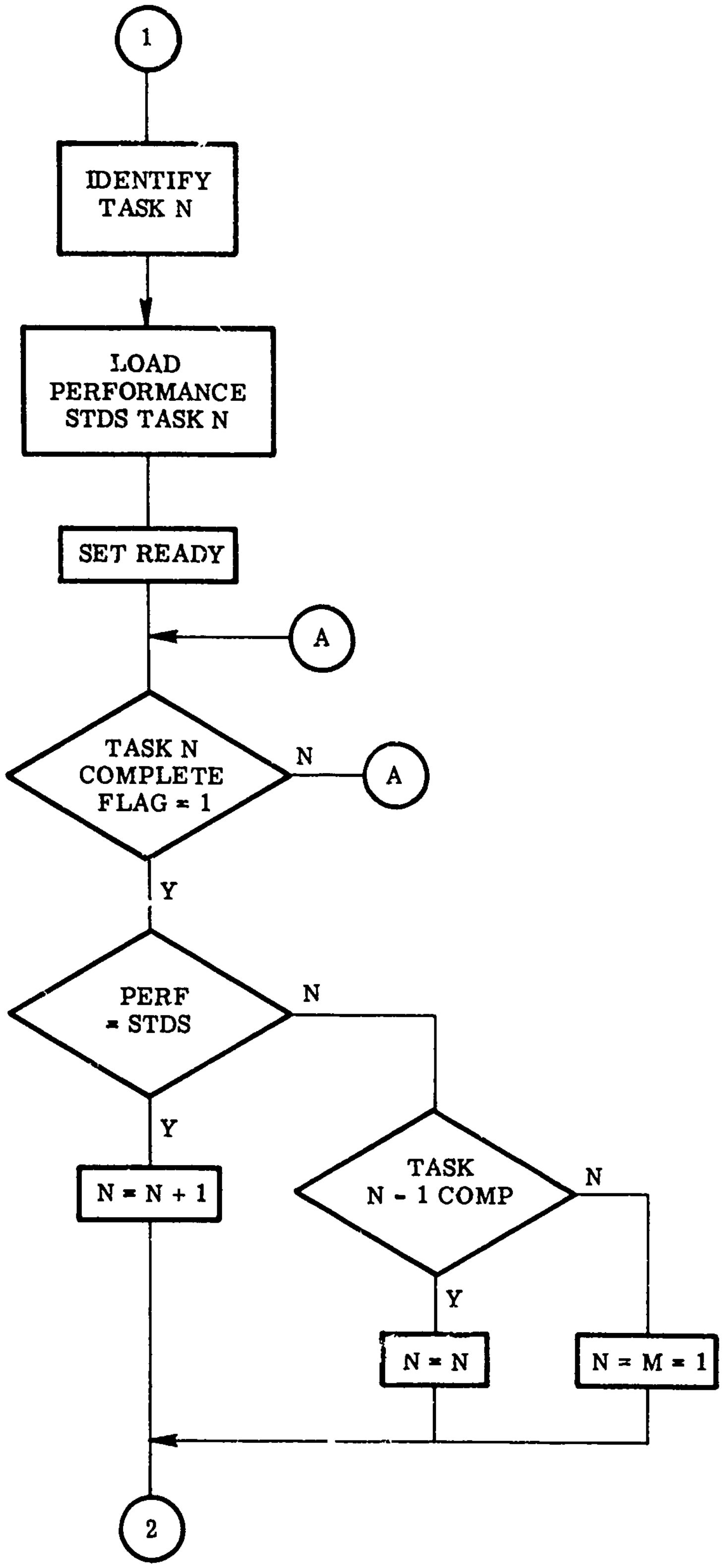


Figure 55 SIMPLIFIED ADAPTIVE TRAINING SEQUENCE

legitimate part of the repertoire of studies to be performed in conjunction with the research simulation facility.

Another approach to the "self-confrontation" concept is to provide a record and playback capability within the computer capacity of the simulator. In this situation, at the discretion of the student or his instructor, it would be possible to call upon the simulator to repeat or play back portions of the student's performance. Various methods may be employed to achieve this. Among the most promising are the use of magnetic tape to record previously flown exercises and the autopilot replay method which, of course, inserts human time lags, etc. These methods may be used also to "demonstrate" the correct technique or illustrate the consequences of incorrect technique.

Additional provisions should be included for computerized analysis feedback. Several methods for which provision must be made include prerecorded audio messages and computer-generated alphanumeric data displayed by a CRT.

11.3.3 Adaptive Training

The concept of self-paced, proficiency-based training should be incorporated into the UPTRSS facility. With an adaptive technique a constant difficulty level can be maintained from the beginning to the end of the learning period. This constant error rate throughout the learning process should be automatically maintained as a function of the trainee's performance, and not the instructor's opinion. Since the state of development of such adaptive systems is still at laboratory level, considerable research into the subject should be one of the primary research areas of the UPTRSS.

Research into the adaptive training techniques should be able to accommodate two distinct categories of undergraduate pilots. The first category would include those trainees who have never flown before or have had only a minimum amount of training. Trainees in this category would find trainer aircraft such as the T-37 too complicated to fly for their experience level even under ideal conditions. The second category would include the trainees who have had sufficient experience to be able to fly the T-37 or similar aircraft under ideal conditions with some degree of proficiency. In order that the learning efficiency for both these categories of trainees be at an optimum value, different types of adaptive training systems are required.

For the category of trainees who have had a minimum of flight training, the research facility should have the capability for researching their learning efficiency by varying the task complexity. Since the simulator

is already too complex to fly even with ideal environmental conditions and no malfunctions, it will be necessary to be able to assist the trainee to a varying degree as he progresses in the learning process. Several approaches to providing the required assistance should be considered. One approach would involve having the capability of varying the stability terms in the simulated flight equations. Related work in this field has been reported by Dr. E. M Hudson.* Another approach would be to use the autopilot to assist the trainee. For this approach several variations exist — e.g., assist about the three axes (roll, pitch, and yaw) or assist about two of the axes while the trainee practices to improve his proficiency about the third, or any combination of autopilot assistance for a particular axis. Similarly, flight simulators have the capability of locking independent axes in the equations of motion. Related investigations have been reported by R. E. Flexman, et al., concerning the application of such techniques.**

When the trainee has reached the degree of proficiency at which he can fly the T-37 aircraft under ideal conditions, a second type of adaptive training system is required. In order to continue the learning efficiency at the optimum rate, methods of automatically varying the environmental conditions and inserting malfunctions are necessary. The insertion of these variants should be controlled by a permissive enabling system, designed to allow only those variants that are appropriate to that portion of the training session to be inserted. The UPTRSS facility should have the capability of readily reprogramming the sequence of insertion of these permissive variants and their relationship to the trainee's progress.

Associated with any adaptive training system is a requirement for both trainee and instructor feedback. This feedback should be automatic and in real time for both the trainee and the instructor. While the instructor's feedback can be a visual presentation utilizing a CRT or hard-copy printout from a line printer or teletypewriter, it is almost essential that the feedback to the trainee be aural. Aural feedback is recommended to minimize the trainees' distraction from his assigned task.

Several audio feedback systems are available on the commercial market. One such system has a sequencer module capable of storing up to 1000 audio messages, with each message being up to 10 words in length. The audio storage is accomplished by using photographic film to record 189 words and/or syllables; a photosensitive readout system is used for the playback of the recorded words. Associated electronics permit communication with the sequencer module which commands the audio unit

* Adaptive Training and Non-Verbal Behavior - NAVTRADEVCEN 1395-1
** Synthetic Flight Training System - NAVTRADEVCEN 1948, April 1968

to reproduce the prerecorded sequence of audio words. The maximum access time to any word or syllable is 533 milliseconds, which is also the time required for the previous word to be played out, thus eliminating time lags between words. This system is available from United Aircraft Corporate Systems Center.

Before any adaptive training system can be implemented, it is necessary first to have developed a system to measure and score the trainees' progress. Research into the development of techniques for scoring or evaluating trainees was not considered in this program.

11.3.4 Automated Instructional Systems

The ultimate development in the areas previously outlined is the completely automated system. As each feature is developed into a usable entity, it would be integrated into a fully automated system. As facility research in adaptive techniques advances, other features can be built into the systems to provide more and more automation. These items might include:

1) Initialization
2) Real-time displays
3) Recording devices
4) Short-term evaluation
5) Long-term evaluation

The capability of the UPTRSS should be such that this type of system can be accommodated. In addition, modular building block devices should be used extensively so that future additions are at low cost levels.

11.4 DEVELOPMENT OF UPTRSS SPECIFICATION REQUIREMENTS

It is recognized that the UPTRSS advanced training area is a field in which many techniques and studies may be evaluated, not necessarily in line with those surveyed above, and thus no specific hardware or software recommendations are made. However, as Section 5 indicates, provisions for capability in this area have been made, based on available information and projections as indicated previously.

12. SITE REQUIREMENTS AND FACILITY CONFIGURATION

12.1 FACILITY BUILDING

12.1.1 Structural Considerations

A basic ground rule for a facility housing training equipment subject to motion is that the motion system be secured as rigidly as possible and not transmit noise and unwanted vibrations to the rest of the complex. Thus the ideal is a complex with the motion bases at ground level, or excavated levels if the terrain permits, such that very high floor loadings can be economically accommodated merely by employing a conventional reinforced concrete floor.

Another desirable structural feature is placement of walls and partitions to serve dual functions and house columns to minimize unsupported spans. A significant reduction in the structural requirements of the building is achieved by making each station which contains equipment requiring large lift-trucks and hoists directly accessible to the outside, so that it is not necessary to transport the equipment through the building.

12.1.2 Facility Layout

In determining site requirements and facility configuration, an attempt has been made to fit all of the individual components of the complex into the most functional arrangement possible under the constraints of:

1) Minimum floor space

2) Minimum cable lengths

3) Isolation of noisy units from trainee/instructor area

4) Isolation of high-heat-generation equipment

5) Shielding of electrical "noise susceptible" units

6) Location of entrance and exit to minimize distraction due to traffic

7) Location of work areas near more trouble-prone units yet away from main service areas

8) Isolating portions of the complex within an enclosure for zone air conditioning

9) Conformance to MIL-STD-803 requirements for Human Engineering Design Criteria

10) Possible nesting or grouping of units of similar size and clearance requirements

11) Ease of installation by location of larger units closer to main equipment entrance doors

12) Relationship to facilities such as water, air, electric power inlet, loading docks, equipment rooms, etc.

13) Means of excluding personnel from areas exposed to hazards (motion, radiation, etc.) and capability of monitoring hazardous areas

14) Growth capabilities and facility conversion for future equipment

15) Provisions for operating moving equipment (fork lifts)

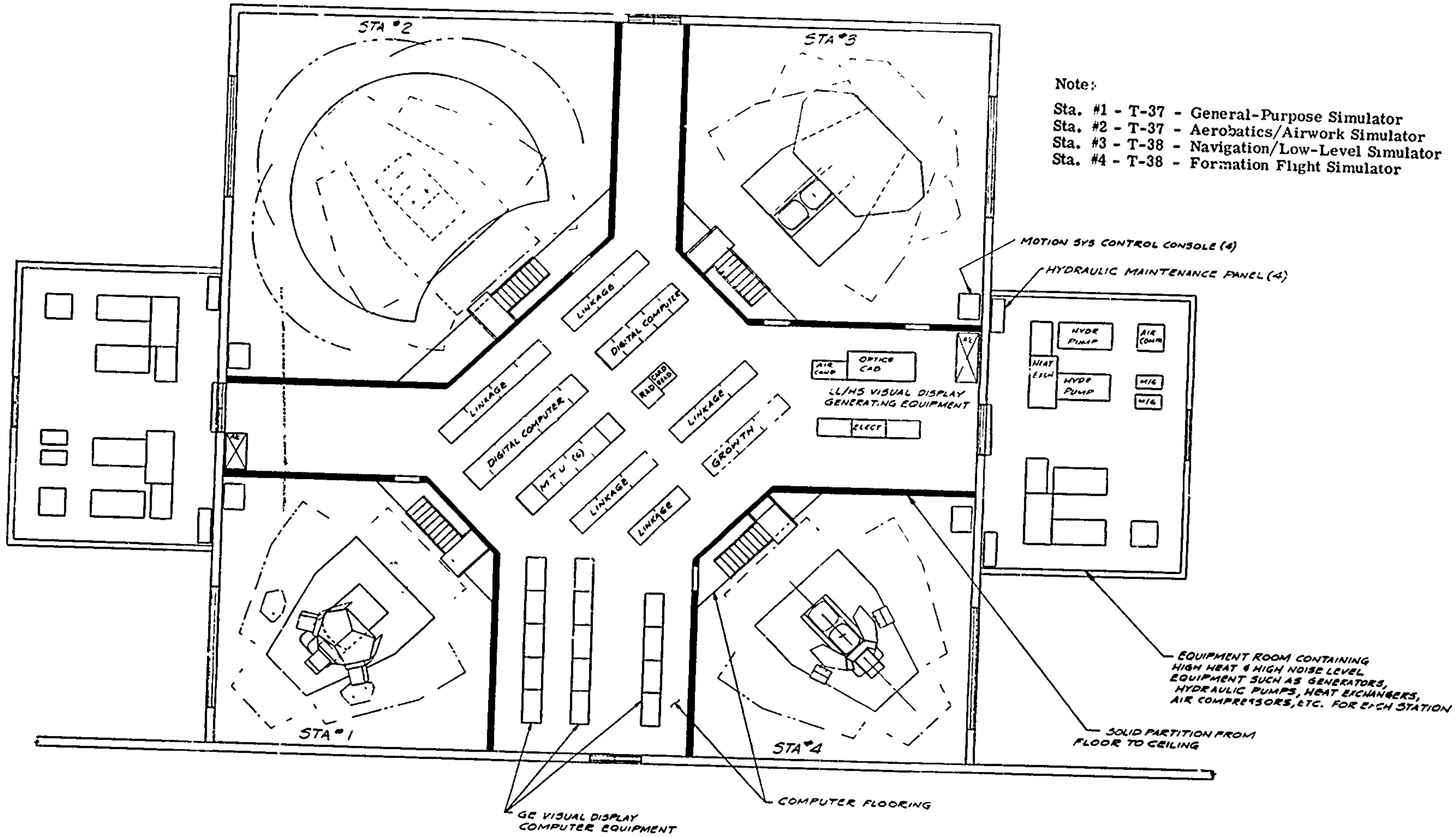
16) Provisions for briefing rooms, and maintenance areas

All of these factors must be weighted in arriving at an optimum floor plan. Ideally, scaled models or paper cutouts would be positioned and superimposed upon a known simulator facility layout, such as a "Standard Air Force Building." Seldom do any two installations reflect the same floor plan because seldom are the parameters weighted in the same way.

In weighting these factors to establish a recommended UPTRSS layout, consideration must be given to the fact that the facility will exist for research purposes, and the proposed layout (see Figure 56) has been optimized to provide the maximum working efficiency while also fulfilling the majority of the subsidiary items on the list.

The facility proposed makes use of the high-ceiling areas required for the visual/motion combinations to accommodate a mezzanine level suited for instructor and experimentor monitoring and direct entry from instruction briefing rooms to flight stations. Also, from a safety standpoint, any entry to the trainee station can best be monitored from this elevated position. Gates should be electrically interlocked to warn of intrusion into hazardous areas (see Section 8).

Maintenance provisions have been considered in keeping the "heavy machinery" in the equipment rooms. Individual power packages prevent total shutdown of training during preventive maintenance or repairs on individual units. A noteworthy feature is the direct access to trouble areas for each station without affecting other station operations.



Note:

Sta. #1 - T-37 - General-Purpose Simulator
Sta. #2 - T-37 - Aerobatics/Airwork Simulator
Sta. #3 - T-38 - Navigation/Low-Level Simulator
Sta. #4 - T-38 - Formation Flight Simulator

Figure 56(1) GENERAL ARRANGEMENT OF UNDERGRAUDATE PILOT TRAINING RESEARCH SIMULATION SYSTEM – GROUND LEVEL

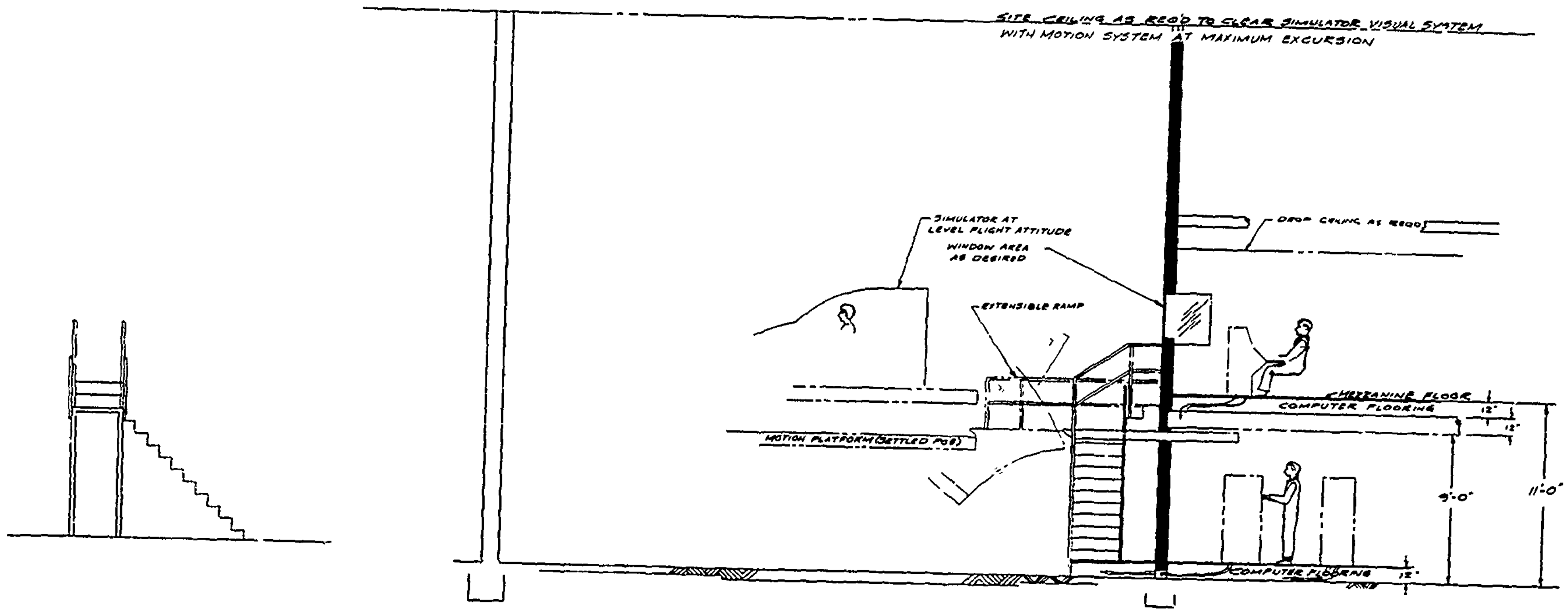
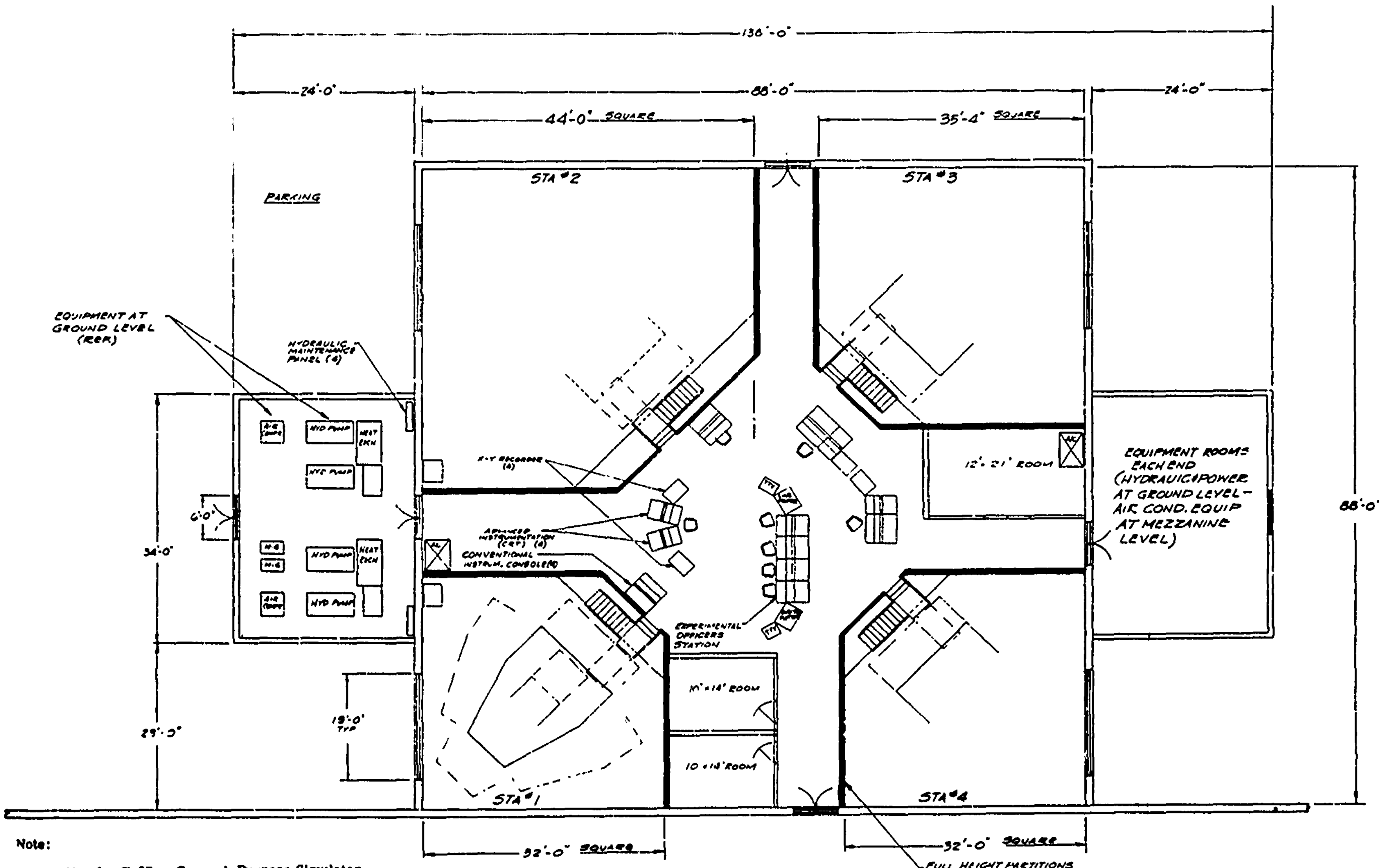


Figure 56(2) ELEVATION VIEW OF TYPICAL UPTRSS SIMULATOR STATION



Note:

Station No. 1 - T-37 - General-Purpose Simulator
Station No. 2 - T-37 - Aerobatics/Airwork Simulator
Station No. 3 - T-38 - Navigation/Low-Level Simulator
Station No. 4 - T-38 - Formation Flight Simulator

Figure 56(3) GENERAL ARRANGEMENT OF UNDERGRADUATE PILOT TRAINING RESEARCH SIMULATION SYSTEM — UPPER LEVEL

Replacement of major components is made possible by specifying large access doors at each trainee station, directly accessible to the outside.

Floor mounting of motion system bases permits economical provisions for high loading. Computer flooring in all except trainee stations and equipment rooms eliminates cable ducts, which tend to limit the arrangement and versatility of a complex. It also simplifies the direction of cooled air to critical heat-producing cabinets by serving as an air-conditioning plenum. The partitions shown permit individually controlled lighting for each trainee station plus more complete acoustic isolation. They also break up the large expanse for the high-bay area, simplifying the structural requirements for the facility.

The diversity of the systems depicted demonstrates the adaptability of the facility to various future systems and growth with minimum disruption.

12.2 FACILITY SERVICES

12.2.1 Operating Power Requirements

The UPTRSS operating power requirements cannot be accurately predetermined because of the extremely wide range of combinations of simulation features subject to evaluation.

The visual systems, for instance, range from point-light-source presentations to the seven-window Farrand infinity-image display. Motion systems may range from 15-hp systems to a 150-hp system such as the Link six-degree-of-freedom system, or possibly even larger, if selected by the using agency. The digital computer shown can be shared, and perhaps its power requirement is the best figure for sizing prediction; the figure projected for three typical computers (Sigma 5) is approximately 35 kva. This, however, is typically a small part of total power. Linkage, test equipment, lighting, power supplies, recorders, and visual and motion systems boost the figure to at least 100 to 150 kva per trainee station. In the final analysis, each item must be tabulated for duty cycle, starting overloads, power factor, and growth contingency. Preliminary estimates appear as follows:

Computer	32 kw
Linkage	30 kw
Visual	40 kw
Motion	240 kw
Air Conditioning	48 kw

400 hertz power		12 kw
F... lighting, test, etc.		40 kw
	Total	442 kw

For comparison, the following power estimates are given for current simulator programs:

FB-111 Mission Simulator	116 kw	
FB-111 N/B Trainer	89 kw	(no visual, no motion)
F-111D Mission Simulator	125 kw	
F-4C WST	115 kw	(no visual, two-degree-of-freedom motion)
Total	445 kw	

Note that these simulators all use small motion systems, or none at all, and do not include air conditioning equipment.

12.2.2 Air Conditioning

The configuration shown will accommodate a zoned air conditioning system mandatory to attain comfort conditions for areas of different exposure conditions and internal heat load conditions.

The high-heat-producing equipment should be located to permit exhausting the heat directly to the outside. The configuration shown permits forced ventilation of the equipment room to the outside without adding the additional heat load to the air conditioning system. Water savers or air-cooled units should be employed if the availability of water as a cooling agent renders such action feasible.

The complex is adaptable to either a site air conditioning system or a separate system designed for this addition alone. The partitions, ceilings, and computer flooring can be built to accommodate the ducting required to attain comfort conditions and controlled environment as deemed efficient for the training program and equipment operation. A practical location for the air conditioning systems would be above each equipment room.

The nesting and grouping of the equipment should result in a considerable saving of air conditioning over that required for less compact arrangements. Obviously the sizing of the units will be dependent upon the computer, visual systems, motion systems, programs being evaluated, and the geographical location of the facility.

A preliminary air conditioning estimate for the complex shown is as follows:

Computer Loading	32 kw	
Linkage, Power, etc.	30 kw	
Visual Systems (4 @ 10 kw)	40 kw	
Motion System (4 @ 15% x 80 hp)	36 kw	
	138 kw x .285 =	40 tons
Space load at 300 sq. ft/ton		25 tons
	Total Requirement	65 tons

12.2.3 Auxiliary Services

In addition to air conditioning and electrical power, site facilities must contain cooling water and pumping facilities to cool the hydraulic pumps and air conditioning equipment.

Preliminary estimates of cooling water for the hydraulic pumps are approximately 7-1/2 gallons per minute per system, or 30 gallons per minute for all four systems. The air conditioning units may require, by rule of thumb, 3 gallons per minute per ton, or 195 gallons per minute. Thus the facility requirement will total 225 gpm for a 10° F temperature rise and 85° F inlet temperature. The air conditioning system need merely overcome head and line pressure, but the hydraulic pumps require a supply pressure of 40 psig. Although the UPTRSS is expected to be built in the Southwest, the site facilities and the availability of natural water sources will dictate the feasibility of the water-cooled approach. If it is prohibitive, air-cooled units may be specified at the approximate cost of a 25% increase in operating power consumption.

12.2.4 Facility Arrangement for Initial Procurement

The arrangement shown in Figure 56 represents the final recommended UPTRSS facility. It is adaptable to being equipped and operated in stages. That is, half of the simulator equipment can be procured, housed, and operated until such time as further budgeting permits procurement of the complete facility. Such an initial layout is shown in Figures 57 and 58.

The wall through the center from floor to ceiling can be specified as temporary and discarded, or, more logically, the initial plan may include the rough construction of the balance of the main building, with

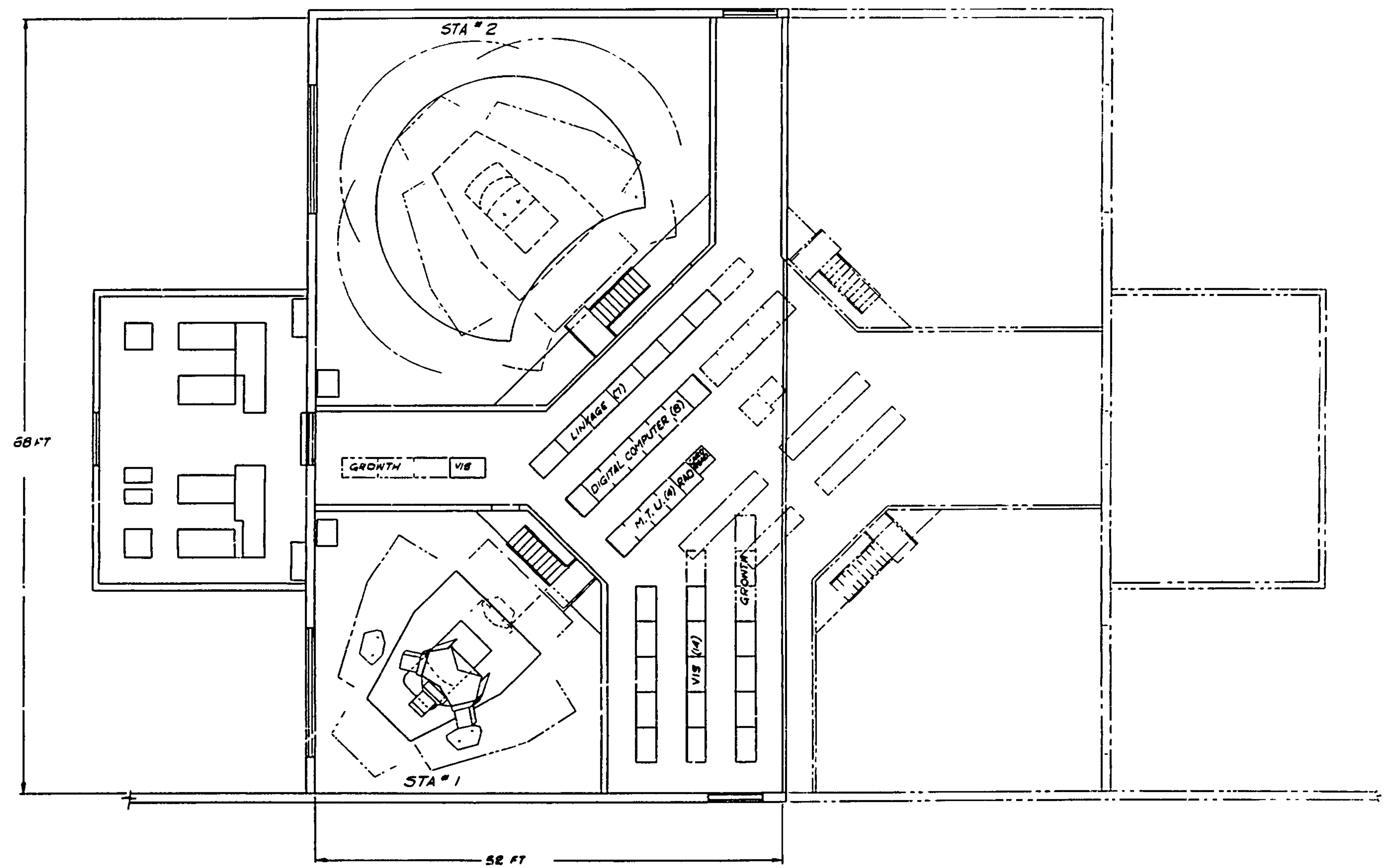


Figure 57 UPTRSS INITIAL PROCUREMENT, LOWER LEVEL

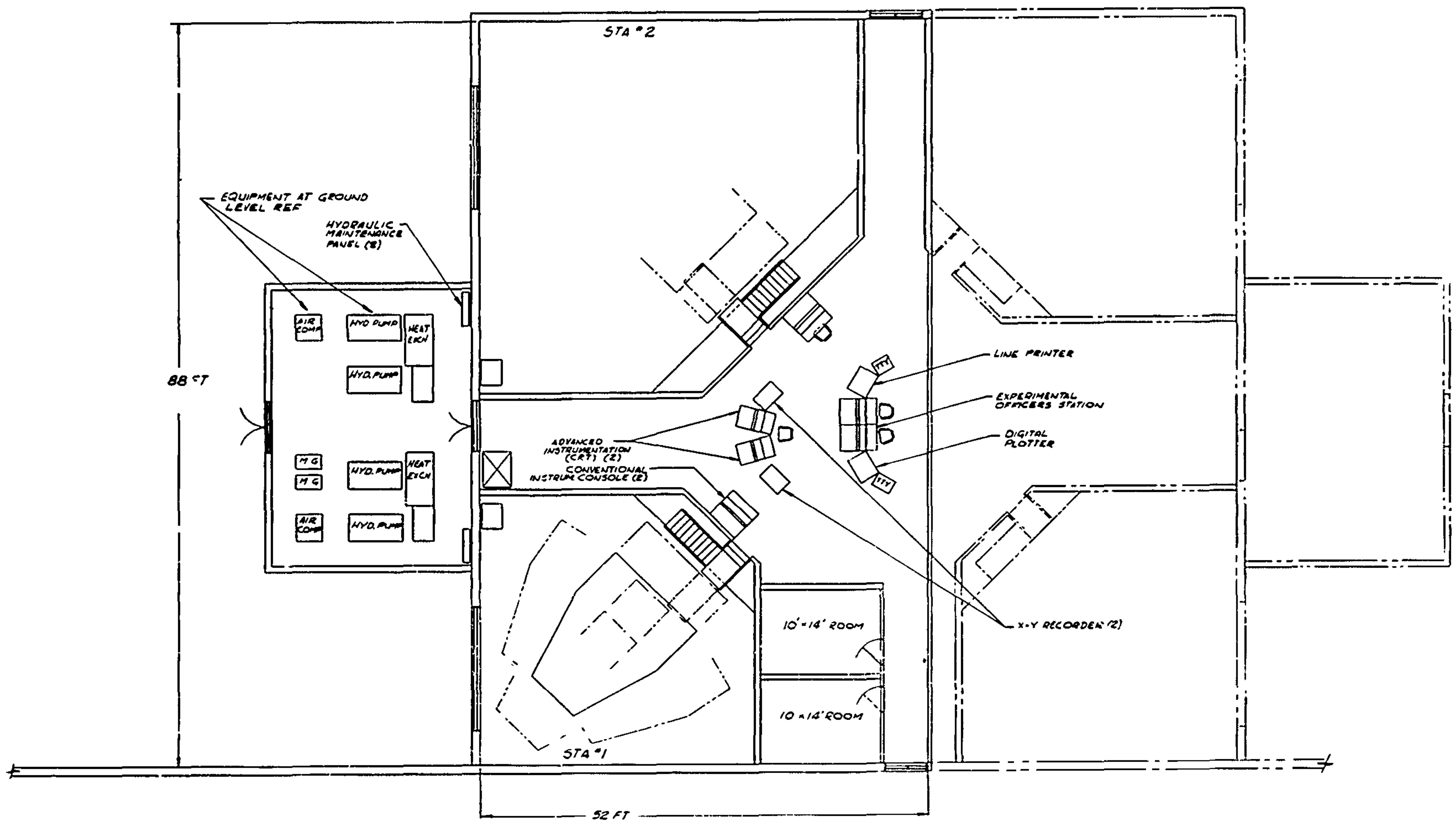


Figure 58 UPTRSS INITIAL PROCUREMENT, UPPER LEVEL

the equipment room building, interior finishing of the right-half, air conditioning, and equipment procurement for the balance of the complex to be completed as funds become available. In the latter case, the temporary rooms may serve other functions during the interim period to justify this approach.

The modular concept would adapt well to this arrangement because the original plan calls for individual equipment rooms and air conditioners on each side to serve their respective halves of the facility.

The estimated power required for this initial larger "half" of the UPTRSS facility is as follows:

Computer	20 kw	(2/3 total)
Linkage	15 kw	(1/2 total)
Visual	20 kw	(1/2 total)
Motion	120 kw	(1/2 total)
Air Conditioner	30 kw	(.6 total)
400 hz power	6 kw	(1/2 total)
Site Lighting, Convenience Outlets, Test, etc.	24 kw	(.6 total)
Total	235 kw	

In other words, the electrical power provisions should be slightly more than half of those for the total requirement.

The air conditioning for this initial arrangement would also be slightly more than half of the total complex requirement, or approximately 40 tons, estimated as follows:

Electronics	20 kw	
Linkage	15 kw	
Visual	20 kw	
Motion	18 kw (15° x 2 x 80 hp x 3/4)	
	73 x .285 = 21 tons	
Area load		19 tons
Total		40 tons

13. MAINTENANCE PROVISIONS

13.1 INTRODUCTION

Careful attention to maintainability requirements is essential to the attainment of a high level of availability of complex systems such as flight simulators. The contractor's responsibilities are threefold:

1) Design to Reduce Maintenance — The equipment designer has many opportunities to reduce maintenance requirements. Careful attention to detail and the application of reliability and maintainability guidelines to each design decision can significantly reduce the maintenance requirements and thus improve availability. Some of the guidelines which should be followed are:

a) Choose the most reliable component available for each application so as to reduce failure rates.

b) Search for a single component to accomplish a task rather than an assembly of components. For example, use integrated circuits rather than discrete-component logic modules.

c) Use components which do not require periodic servicing to reduce preventive maintenance requirements. For example, use solid-state devices rather than electromechanical devices wherever possible.

2) Design to Facilitate Maintenance — Simulator availability can be greatly enhanced by the incorporation of design features which facilitate maintenance and thus reduce downtime due to failures. All components and assemblies should be readily accessible for inspection and/or replacement. Plug-in modules should be used to the maximum extent possible to permit rapid replacement of a defective module. An adequate number of test points should be provided to permit every signal to be monitored at appropriate points throughout the simulator. Standardized parts and assemblies should be used wherever possible to facilitate spares provisioning and thus help assure that spare parts will be available when needed.

3) Design Special Maintenance Aids — Adequate test and repair facilities should be provided to minimize the amount of time required to detect, isolate, and repair a defective component or assembly. In particular, automatic test facilities should be built into the simulator wherever possible. These facilities should be so designed that they do not contribute noticeably to the overall failure rate of the simulator. The digital computer should be utilized wherever possible for these automatic test features to minimize the additional hardware required. The bulk of the task should be accomplished by computer software developed for that purpose.

Documentation is an equally important aspect of the test and repair facilities provided with the simulator. Maintenance manuals should provide ready access to information needed for troubleshooting and repair of the simulator. All manuals should be organized to minimize the need for cross-referencing during any specific maintenance task. All procedures should be clearly defined in the maintenance manuals in a complete and concise manner.

13.2 ACCESSIBILITY

Designing the simulator so that all portions are readily accessible, particularly those areas requiring frequent servicing, will contribute to improved maintainability. This will be especially important for a research system in which almost any portion of the simulator will be subject to modification from time to time.

In computer and electronics cabinets, test points should be readily accessible and conveniently located so that a technician can take measurements and observe waveforms rapidly when diagnosing system troubles. Circuit cards should be readily removable for rapid replacement of cards suspected of malfunctioning. Design of panels in the cockpit and instructor station should permit rapid replacement of indicators and other components subject to failure. Hinging of panels can be helpful where space permits.

Good maintainability practice requires that wherever possible any component be accessible without necessitating removal of other components. This guideline is often difficult or impossible to adhere to fully in the design of elaborate visual simulation systems. The technical requirements for location and spacing of projectors, lenses and other optical devices with respect to the cockpit viewing windows may require extremely tight packing of equipment. One visual system requires that the simulated cockpit be so tightly nested into the visual equipment that it is necessary to mount the cockpit on tracks to permit withdrawal of the cockpit from the visual equipment, not only for maintenance but even to permit trainee ingress and egress. This is a good example of the extreme measures which are sometimes required to provide the necessary accessibility.

13.3 COMPONENT RELIABILITY

A few examples of methods to reduce the number of overall equipment failures include the following:

1) Integrated circuits should be used wherever practical. This reduces the total part count which in turn improves reliability.

2) Silicon solid-state devices should be used extensively. Silicon devices operate more reliably over a wider temperature range than do other devices.

3) Corrosion-free, gold-plated terminals should be used.

4) Electromechanical devices such as servos, which are subject to wear, vibration, and dust, should be avoided wherever possible.

5) Fine filters should be used in the hydraulic system for prolonged life.

13.4 MINIMIZING SERVICING REQUIREMENTS

Every effort should be made to incorporate components and systems which require a minimum of periodic servicing. Certain mechanical units including computer peripherals such as punched card readers, line printers and magnetic tape units, for example, will probably always require periodic cleaning, adjustment lubrication, etc. However, improvements can be made even in these areas. For example, use of permanently lubricated, long life bearings can reduce or eliminate the need for frequent lubrication.

13.5 STANDARDIZATION

Standardization of components, or assemblies, subject to replacement in a training device can of course have a definite effect on maintainability of the device and on the logistics problems associated with obtaining replacement parts. Standardization may involve use of military standard parts or parts which can be replaced by military standard parts, use of vendor standard parts already in use in other devices operated by the using activity, or at least standardization to the extent of repeated use of certain parts and assemblies within a given device.

Specification requirements for standardization should at least consider the fact that the state of the art is changing very rapidly, particularly with respect to solid-state devices and microelectronic circuit modules. Some of these changes are having drastic effects in areas of circuit miniaturization, reduced cost and increased reliability. These changes will have a major effect on maintenance techniques. Frequently there is a time delay between the availability of new components and the time they receive military approval. Certain components of good commercial quality often provide essentially the same reliability as their MIL-approved counterparts but at substantially lower cost. The portion of simulator procurement specifications relating to standardization, maintainability, materials, etc., should not be so restrictive as to preclude, or negate the value of incorporating those state-of-the-art advances in components which could make significant contributions in the areas of improved reliability and lower maintenance cost.

13.6 USE OF ACTUAL AIRCRAFT PARTS

Whether or not to use actual aircraft parts, particularly indicators, in flight simulators is always a matter requiring serious consideration. In general, it would appear that maintenance can be improved and cost reduced by using actual aircraft parts in cases where the simulator is to be installed at or near a base from which a number of corresponding aircraft are flying and where adequate spare parts and maintenance facilities are already available. This statement assumes that it is technically feasible to use the aircraft parts in the simulator.

13.7 INTERFACE JUNCTION PANEL

Experience has shown that a central interface junction panel (essentially a large patch panel), typically housed in its own cabinet, is a valuable asset in simulator maintenance. The majority of all electrical connections between any section of the simulator and any other section are brought through the interface junction panel. Each connection enters the panel via one cable and leaves via another cable, with the circuit completed between the fixed cable connectors by means of a jumper lead. High quality, gold-plated jumper terminals provide excellent connections but are readily removable when changes are necessary. This ease-of-change feature will be of special importance in a research system where changes may be considerably more frequent than in normal simulator usage. Interface leads which typically do not pass through an interface panel include critical pulse and video signal leads and heavy power distribution wiring which are better run directly.

Use of the interface junction panel virtually eliminates the need for rework in cables, thus removing this potential source of trouble. All connections in the interface panel are readily accessible so that changes can be made much more readily than would be possible otherwise. Although the jumper connections in a typical interface panel are not designed especially for use as test points, it is sometimes convenient to use them for this purpose. It is often helpful if a small portion of the interface panel is reserved and specially designed to provide specifically required test points at which a recording oscillograph or other measuring equipment could be connected. This would be particularly true in the case of a research system.

On at least one occasion, the calendar time required to incorporate a major modification in a large simulator was drastically reduced by building a duplicate interface panel and completely wiring it and testing it to the new configuration at the factory. Then on "change-over day," the simulator interconnections were changed in a matter of hours by unplugging the cable connectors from the back of the panel, replacing the old interface panel with the new one, and reconnecting the plug-in cables.

13.8 TEST CAPABILITY

13.8.1 Self-Test Capability

The simulator should be capable of self test to the maximum extent practicable. This test capability should, as a minimum, enable an operator to determine rapidly that the vast majority of the simulator is or is not operating properly. In addition, this test capability should also enable the operator to locate the area of the trouble for faults detected in large portions of the simulator insofar as this capability can be incorporated at a cost commensurate with its value.

The limiting factors regarding the extent of built-in test features include the increase in cost and the decrease in reliability resulting from the hardware which may be required.

The self-test capability which is built into a training device should be used to augment, rather than replace, the more conventional maintenance features normally provided. These standard test features (including test points, adequate documentation, etc.) will still be required because an economical and reliable set of self-test features cannot be expected to locate all possible troubles and because the self-test features themselves are subject to failure.

13.8.2 Test and Diagnostic Programs

Fortunately, it is possible in a typical digital flight simulator to make use of the digital computer itself to test, or at least verify the proper operation of, large portions of the simulator. This is so because during normal operation of the simulator, the simulator is controlled by outputs from the digital computer. Therefore, provided that the digital computer is operating properly, it is quite convenient to use diagnostic programs (or more properly, hardware test programs) to rapidly perform a readiness test of much of the simulator. This type of test is of particular interest in that, as described here, it requires little or no additional hardware, but rather only additional computer programs. However, as described here, it does require operator activity to operate input controls under test and to read output displays under test.

Regarding digital computers themselves, most modern digital computers are, or can be, supplied with a set of diagnostic programs which can be used to verify proper operation of the computer and to speed the isolation of any fault which may occur. Certainly it is reasonable and desireable to insist that the digital computer supplied with a simulation system include such a set diagnostic programs. These programs should include test routines for all computer peripheral equipment such as magnetic tape units, punched card readers, teletypewriters, etc. Obviously, the procedure would

be to verify proper operation of the digital computer before using the computer for tests of the balance of the simulator.

13.8.3 Built-In Test Features

It is difficult to generalize regarding the extent to which additional hardware should be built into a flight simulator to provide a self-test capability or to aid in troubleshooting.

The final decision can best be made by the equipment designers based on the type of equipment involved, the intended use of the equipment, and the maintainability requirements detailed in the procurement specification. Other factors to be considered include the technical feasibility of the features and the relationship between the cost involved and the resulting improvement in maintainability.

13.8.4 Subsystem Test Panels

For each complex subsystem of the simulation system, particularly for analog (non-digital) subsystems such as the motion simulation system and the visual simulation system, for example, it would generally be desirable to provide each such subsystem with its own individual control panel. The panel would include provisions for switching the system to either computer-controlled or manual modes as well as controls and indicators for operating the system in the manual mode.

Such a manual control feature would be especially valuable in systems for which some of the following are applicable:

1) The system requires frequent or long-time-consuming maintenance

2) The system is not so complex as to make worthwhile manual control difficult or impossible

3) The system can be expected to undergo experimentation or modification which would involve system changes requiring lengthy periods of testing or debugging

The advantages of such a system control panel for relatively "independent" systems include the following:

1) The computer would not be tied up for long periods during which it would be controlling the system under test. Thus, the computer could be used simultaneously for various other tasks. (Admittedly, it is within the state of the art to write a test program to control one system under test which could operate in the computer simultaneously with another set of

programs involving other totally unrelated tasks. However, the costs and other problems related to such sophisticated programming would generally far exceed those involved in providing a relatively simple system control panel.)

2) Maintenance and test of the system could proceed even when the computer is either inoperative or not available for some reason. This could be the case with one computer complex driving more than one cockpit.

3) In some cases the test personnel skilled in the analog system under test, but not necessarily skilled in the control of digital computers, might find it much more convenient to operate the system from a system-oriented control panel than from the general-purpose controls of the digital computer. Such a device is discussed in Section 8, to exercise the six-degree-of-freedom motion system.

13.8.5 Running Time Meters

In mechanical systems, preventive maintenance is usually required after a specified number of hours of operation. Therefore, inclusion of running time meters in such systems is a convenience in keeping track of when maintenance should be performed.

13.8.6 Voltmeters in Power Supplies

As a starting point in proper simulator operation, it is essential that power supplies provide the correct voltage. Rapid checking of supply voltages can be achieved if each supply includes a built-in voltmeter which constantly indicates the output voltage level. This is particularly helpful on the adjustable voltage DC supplies which are widely used in simulators. For those supplies in which it is not practical or economical to include a meter, the supply should at least include terminals readily available on the front panel for connecting a portable voltmeter.

If deemed necessary by the using activity, more elaborate methods can be incorporated for checking power supply voltages. One method would be to bring all voltages in the simulator, or in a major subsystem, to a common test panel equipped with a selector switch and a built-in voltmeter. The operator could then cycle through the selector switch positions and check each individual voltage. Or a fully automatic voltage monitoring system could be incorporated which would constantly monitor all supply voltages and provide an alarm when any voltage is out of tolerance.

13.8.7 Amplifier Checker

In modern digital simulators, it is becoming rare to have a large quantity of identical operational amplifiers used in a given system.

However, it should be mentioned that for those cases where this situation arises, it is helpful to include an automatic amplifier checking system.

Such a system can cycle rapidly through all of the amplifiers in the system, performing several go/no-go tests on each amplifier and indicating to the operator which amplifiers, if any, are out of tolerance.

13.8.8 Test Equipment

In addition to the standard and special test equipment usually furnished with a simulator (such as voltmeters and oscilloscopes) for use in routine maintenance and occasional minor modification of hardware or software, a research system would require unusual test equipment of the sort used in initial test and debugging during prototype development and acceptance testing (such as multi-channel recording oscillographs), as well as equipment to measure and/or record parameters not normally measured in routine training (such as a built-in system for measuring force and displacement in the control loading system for the primary flight controls).

13.8.9 Specially-Designed Test Equipment

Certain pieces of special test equipment have been devised which are very helpful in simulator maintenance and used to reduce the time required for testing and debugging of new or revised computer programs. Inclusion of such devices would be particularly important in a research system where software revisions might be quite common. Two such devices are a portable test unit (often referred to as a decimal readout unit), used primarily for examining the contents of a desired core memory location, and a parameter set panel for controlling the value of certain computed parameters during software tests. These units plug in and operate as though part of the simulator during use.

An assembly tester (see Section 13.8.10) is also highly desirable for use in testing and troubleshooting of assemblies, particularly plug-in circuit cards.

13.8.10 Assembly Tester

It seems advisable that the maintenance equipment for the UPTRSS should include an assembly tester which can be used for testing circuit cards and for diagnosing circuit card faults, for at least the majority of the circuit cards used in the simulator. For maximum flexibility, the tester should be a self-contained, independent unit capable of operation regardless of whether or not the simulator is operating.

Due to the large number of electronic circuit cards in a flight simulator and the complexity of these cards, a useful assembly tester can be

a complex and expensive item. Furthermore, the complexity of the test inputs required to test a given circuit card suggests that at least for the commonly tested cards, the test setup should be automated, both to greatly reduce the setup time and to reduce the chance of the card being damaged as a result of incorrect test connections.

A definite, finite limit must be put on what is expected of an assembly tester, if the cost and complexity are to be kept within reasonable bounds. A number of recent flight simulator specifications have included a requirement for a "voltage test unit", a term which apparently originated in the days of analog simulators. The specifications seemed to imply a remarkable device capable of thoroughly and conveniently testing virtually every electrical component and assembly in the simulator under conditions identical to those in which it is used in the simulator. While such a device undoubtedly could be designed, its cost might well exceed its value. A more reasonable approach would seem to be to require an assembly tester specifically designed to conveniently test only the more common circuit cards. The tester should also include a voltage and signal output panel to permit partial testing of less common assemblies using manual, breadboard-type connections.

Rather than specify the assembly tester in the basic simulator procurement specification, it would seem that a preferable approach would be to have the assembly tester included with the aerospace ground equipment (AGE) which is normally recommended by the simulator manufacturer during the development phase of a simulator contract. By this time in the program, the manufacturer would be in a better position to know the exact types and quantities of assemblies to be used in the simulator and he could therefore better propose a device which would provide maximum usefulness at reasonable cost.

13.9 OTHER CONSTRUCTION FEATURES

Other features to make maintenance faster and more convenient include the following:

1) A maintenance intercommunication system to facilitate team efforts.

2) Convenience outlets in each cabinet or major assembly for connecting test equipment, soldering irons, etc.

3) Slide mounting of large assemblies requiring frequent servicing, where appropriate.

4) Adequate labeling of cable terminations.

5) Color coding of wiring, where appropriate.

6) Test points, or equivalent terminals, readily accessible for measurement of all critical signals.

7) Quick-opening fasteners for cockpit skins.

8) Use of plug-in modules for electronic circuitry wherever possible.

13.10 SPARE PARTS PROVISIONING

If repairs are to be made rapidly to get the training device back into operating condition following a failure, it would seem essential that each installation site be stocked with an adequate supply of spare parts and assemblies, except for military standard parts and other common items which may be readily available through existing channels. This is true particularly for plug-in electronic modules. It is recommended procedure for electronic circuitry to be packaged in plug-in modules wherever practicable to enhance ease and speed of replacement. But much of the advantage gained will be lost if there is not a replacement module available to replace any module which might fail.

One method of troubleshooting complex electronic equipment, such as computers for example, involves isolating the difficulty down to a group of plug-in modules, and then replacing the whole group to get the equipment back in operation quickly, rather than taking the additional time required to determine exactly which module in the group is the defective one. This is so because it is often impossible or uneconomical to devise diagnostic programs or other test methods which will quickly identify the location of a fault any closer than to a group of circuit cards. Therefore, it is essential to have on hand sufficient spare cards to handle any such group replacement. The defective card in the group can be determined later, either on off-line test equipment or in on-line tests during a scheduled maintenance period.

For those replaceable assemblies which are deemed capable of repair in the field at the simulator site, an adequate supply of spare components should be stocked to permit prompt repair of defective assemblies.

14. VENDOR SURVEY

In order to evaluate the current state of the art in simulation, a survey was performed of vendors of simulator systems, subsystems, and related hardware. The letter and attachments forwarded to each of the selected vendors are reprinted on the following pages. A list of the vendors selected is presented in tabular form at the end of the section. The "X" designation denotes a response of some kind, not necessarily containing relevant information. Unfortunately, very little pertinent information on critical areas, such as visual and motion systems, was obtained, and this factor severely limited comparative studies. The complete content of each response can be furnished upon request.

GENERAL PRECISION SYSTEMS INC.
LINK GROUP

BINGHAMTON, NEW YORK 13902 | PHONE 607-772-3011 TWX 510-252-0195

Dear Sir:

Under Contract No. F33615/68/C/1604 to the Department of the Air Force, ASD Wright Patterson Air Force Base, Link Group, General Precision Systems, Inc., is conducting a study to determine the engineering details and design necessary for the establishment of an Undergraduate Pilot Training Simulation Research Facility (UPTSRF). The proposed facility will utilize advanced state-of-the-art simulator techniques to investigate the limits of simulator capability, and to define methods and techniques for maximum utilization in training programs.

At the request of ASD Wright Patterson, and as part of the study, a survey of manufacturers of equipment that could be implemented in the facility is being performed. Your company has been included in this survey. A brief description of the performance requirements for the facility is included as enclosure (1). Enclosure (2) outlines the areas of particular importance in the definition of the facility, and sets forth the information required for each of the categories (where applicable to your products).

Please forward all pertinent information on equipment to the writer. A summary of vendors and information received will be forwarded to ASD Wright Patterson.

Sincerely,

R. L. Taylor, ASD Study Program Manager
Dept. 554

RLT:cs

Encs. - 2

Enc. - 1

FACILITY PERFORMANCE

REQUIREMENTS

RESEARCH

The simulation facility is intended to be used to investigate design features of simulators for training as well as to develop simulator curricula, instructional techniques, to include both automated and instructor assigned performance measures.

For example the facility will be used to study:

1) the level of simulator fidelity required for optimum transfer of training
2) the training concepts associated with the enhancement of skills in novice pilots
3) more precise methods of man/machine performance measurement
4) whether more effective transfer of training occurs when visual and/ormotion cues are provided
5) adaptive training techniques; computer based instructional systems; automatic scoring and monitoring techniques; video self-confrontion, etc.

AIRCRAFT TYPES SIMULATED

a) T 37
b) T 38

TYPICAL TRAINING PHASE

To provide a facility capable of supporting the comprehensive research program envisaged, the following training capabilities are envisaged:

a) Airwork
b) Aerobatics
c) Formation Flying
d) Night Flying
e) Take Off and Landing
f) Taxiing Takeoff and Landing
g) Low-Level Flight

To be included in the survey, responses should be received by August 9, 1968.

Enc. 2

INFORMATION REQUIRED

MOTION SYSTEM

1. Specifications, block diagrams, engineering drawings, etc. of hydraulic motion systems capable of, or being used for, motion simulation.

2. Details of servo valves, actuators, electronic equipment, power requirements, etc.

3. Floor loading, space requirements, load carrying capabilities.

4. Details of maintenance and safety features.

5. Number of degrees of freedom, dynamic and excursion capabilities.

6. Servo loop design, compensation techniques, Bode plots.

7. Rationals and study publications to justify dynamic capabilities, and excursion capabilities for training in the simulation task.

8. Drive signal formulation for control of motion system.

9. Approximate cost and lead time for delivery in the 1970's.

INFORMATION REQUIRED
AURAL SIMULATION

VOICE SIMULATION

1. Specification, block diagrams, circuit diagrams, etc., of systems capable of, or being used for, voice reproduction in flight trainer task.

2. Applicability of system to the on-line flight simulation requirement for V.O.R., G.C.A., and V.H.F. in-flight communication.

3. Number of messages system can store, message length, smallest increment, largest increment.

4. Storage media, local and remote control.

5. Type of message selection, automatic, manual or semi-automatic.

6. Message search or selection time.

7. Space and power requirements.

8. On-line, and/or off-line, local and/or remote, record playback and erase capabilities.

9. Software required if any, iteration rates, storage requirements.

10. Approximate cost, and delivery lead time for procurement in the 1970's.

AIRCRAFT SOUNDS

1. Specifications, block diagrams, circuit diagrams, etc., for computer controlled aircraft sound simulation systems.

2. Method of determining and simulating the frequencies for the following:

   a) Reciprocating, Turbo-Jet and Jet engines
   b) Inverters
   c) Aerodynamic sounds, configuration changes, etc.
   d) Armaments (i.e. rockets, machine guns)

3. Method of synchronization of sounds with action that produces them.

4. Method used to control directivity of sounds.

Enc. 2 cont'd

INFORMATION REQUIRED

COMPUTER

A HARDWARE

I C.P.U

a) Average execution time for the mix,

Load/store	.432	....
Add/subtract	.130	....
Multiply	.060	....
Divide	.0144	....
Branch	.0756	....
Shift	.1062	....
Logical	.1816	....

b) Double Precision and times if less than 24 bit word

c) Number of index registers, time added for indexing

d) Addressing capabilities if less than full memory

e) Number of registers available under program control

f) Provisions available for multi-processor operation

g) Provisions for multi-computer operation

II Memory

a) Memory cycle time, increments available, multiple access provisions

b) Maximum memory size, additional hardware required to expand memory

c) Types of data transfer available (cycle-stealing, fully buffered, multiplexed, etc.)

d) I/O capabilities, interruptability, transfer block size, transfer word size, maximum number of device controllers per channel

B SOFTWARE

a) Available software; compilers, assemblers, diagnostics, traces etc.

C GENERAL

a) Peripherals directly communicable with the computer

b) Approximate cost of main frame with minimum memory and cost of memory increment.

Enc. 2 (cont'd)

INFORMATION REQUIRED

VISUAL SYSTEMS

1. Specification drawings, etc., of visual systems applicable to the flight simulator problem
2. Device type, e.g. camera - Model T.V., trade name
3. Resolution, bandwidth
4. Display size (field of view)
5. Exit pupil size (at observer)
6. Effective distance from observer to displayed image
7. Multi or single display per image
8. Real world or symbolic image
9. Color image available (none, partial, full)
10. Display brightness
11. Compatibility with motion system mounting
12. Size and weight
    a) Image generator
    b) Image processor
    c) Display
13. Approximate size and speed (or standard type digital computer equipment required)
14. Special weather effects available (variable/fixed
    a) Ceiling height
    b) Haze, fog (visibility range)
    c) Cloud cover
15. Area of terrain coverage
16. Limits on freedom of movement within terrain area
    a) Roll
    b) Pitch
    c) Yaw
    d) Lateral
    e) Vertical
    f) Transverse
17. Compatibility with heads-up display devices

Enc. 2 (cont'd)

INFORMATION REQUIRED
CONTROLS/DISPLAYS/PLOTTERS

1. The specification and characteristics of computer oriented man/machine interface systems, e.g. CRT's, keyboards, large screen displays, instruments, etc., technical data to include:
   a) Character writing and input speed
   b) Vector drawing speed
   c) Random position speed
   d) Display update rate
   e) Internal buffer size
   f) Display size
   g) Reliability
   h) Applicable MIL Specs
   i) Equipment size and rack mounting capability, power requirements
2. Methods of generating characters, vectors and other symbols.
3. Multiplexing display capabilities, e.g. split-beam CRT.
4. Multiplexing terminal capability, e.g. several display devices driven from one control unit.
5. Computer interface equipment required to operate the systems.
6. Details of control and software requirements for on/off-line updating displayed information.
7. Cost and delivery lead time of systems for procurement in 1970's, breakout of modular components.
8. Computers with which equipment has been interfaced; addition cost incurred.

The following companies were surveyed and responses were obtained as indicated:

AAI	X	Barry Controls (Div. of Barry-Wright)	
Aero Service Corporation Division of Litton Industries		Bryant Computer Products Div. of Ex-Cell-O-Corp.	X
Ames Research Center	X	Curtiss-Wright, Electronics Div.	
Ampex Corporation	X	Conductron-Missouri	X
Ampex Data Products Co. Computer Products Division		CAE Electronics Division CAE Industries, Ltd.	
Adage Inc.		Chrysler Corp.	
AMF York Div.-General Office	X	California Computer Products, Inc.	X
Astro-Space Laboratories, Inc.		Carco Electronics	
AMP Inc.		Control Data Corp.	
AMP Inc., Capitron Div.		(Computer Div:) Holley Computer Products Co.	
Anderson Laboratories, Inc.		Collins Radio Co.	X
Astrodata Inc.		Computer Instruments Corp.	
Ampex Data Products Co. Computer Products Division		Conrac Corp.	X
Bunker Ramo Corp. Defense Systems Div.	X	Cybertronics, Inc.	
Burtek, Inc.		Control Data Corporation	
The Bendix Corp.		Control Data Corp. Magnetic Prods. Operation	
Burroughs Corp.			
Bell Aerosystems Co.	X	Dalto Electronics, Inc.	X
Beckman Instruments, Inc. (Electronic Instrument Div.)		Dage Electric Co., Inc.	
		Digital Equipment Corp.	X
Bolt Beranek & Newman Inc.	X	Data Processing & Products Div. Hughes Aircraft Co.	

R. B. Denison Mfg. Co.	X
E. I. duPont deNemours & Co., Inc.	X
Digital Equipment Corporation	
A. B. Dick Company	
Digitronics Corp.	X
Epsco, Inc.	
Electronic Associates Inc.	
Electronic Engrg. Co. of Calif.	X
Equipto Enclosure Systems	X
Electronic Memories, Inc.	
Epsco, Inc.	
Ex-Cell-O-Corp. (Bryant Computer Products Div.)	
Fairchild Controls Div. Fairchild Camera & Instr. Corp.	X
Farrand Optical Co., Inc.	
Franklin Institute Research Labs	X
Federal Systems Div.	
Fabri-Tek Inc.	X
Gems Co., Inc.	X
Goodyear Aerospace	
General Electric Co. Industrial Sales Div.	X
Aircraft Equipment Division	
Grumman Aircraft Engrg. Corp.	X
General Instrument Corp.	X
Gerber Scientific Instrument Co.	X
Graphic Controls Corp.	
Hughes Aircraft Co. Connecting Devices	X
Hughes Aircraft Co. Electronic Devices Dept.	
Hughes Aircraft Co. Microelectronics Div.	
Hughes Electronics Co.	
Hydro Systems Co.	
Holley Computer Products Co. (Computer Div. of Control Data)	
Hewlett-Packard Co.	X
Honeywell (Computer Group)	
ITT Cannon Electric Div.	
ITT Electro-Physics Labs Inc.	
ITT General Controls Inc. Midwest Div.	
Information Displays, Inc.	X
IMC Magnetics Corp. (Eastern Div.)	
Indiana General Corp.	
Itek Corporation	X
Informatics Inc.	

Kollsman Instrument Corp.	
Lockheed Aircraft Service Co. Special Devices Div.	
Ling-Temco-Vought, Inc.	X
Langley Research Center	X
Litton Systems (Canada) Ltd.	
LFE Electronics Inc. Commercial Products Operation	X
Lewis Engineering Co.	X
Lewis Research Center	
Melpar, Inc. Special Products Div.	
Marconi Instruments Div. English Elec. Corp.	X
Miles Hivolt Ltd. Old Shoreham Rd.	X
Miles Reproducer Co., Inc.	X
Midwestern Instruments, Inc.	
McFadden Electronics Co.	
Milgo Electronic Corp.	X
Mellonics Systems Development Div. of Litton Systems Inc.	X
MGD Research & Dev. Corp. Subsidiary of Miehle-Goss-Dexter, Inc.	
Memorex Corp.	X
3M Co. - 3M Center	
3M Co. DM & S Div.	
Marquardt Industrial Products Co.	X
North American Philips Co., Inc.	
National Cash Register Co. Industrial Prods. Div.	
Otis Elevator Co.	
Optical Scanning Corp.	
Photomechanisms, Inc.	X
Photics Research Corp.	
Preston Scientific Inc.	X
Precision Instrument Co.	X
Potter Instrument Co.	
Planning Research Corp.	X
Redifon Air Trainers Limited	X
RCA Broadcast & Communications Prods. Div.	
RCA Defense Electronics Prods.	
RCA Electronic Components & Devices	X
RCA Service Co. Technical Products Dept.	X
Raytheon Co.	
Reflectone Division of Otis Elevator	

Redcor Corp.	
Rixon Electronics Inc.	X
Randolph Products Co.	
Sanders Associates	
Scientific Data Systems	
Spitz Laboratories, Inc.	X
Sangamo Electric Co. Capacitor Division	
Servo Corp. of America	
Servo Development Corp.	X
Sperry Rand Corp.	X
Sperry Flight Systems Div.	
Systems Engrg. Laboratories, Inc.	X
Systron-Donner Corp.	
G. T. Schjeldahl Co.	
Sealectro Corp.	X
Soroban Engrg. Inc.	
Stromberg-Carlson Data Processing Div.	
Tally Corp.	
Texas Instruments Inc. Control Products Group	
Texas Instruments Incorporated Apparatus Div.	
Texas Instruments Inc. Semiconductor-Components Div.	X
Univac Division	X
Varian	
Westinghouse Electric Corp. Electrn. Components & Spec. Group	
Wang Laboratories, Inc.	
Wyle Laboratories	
Xerox Corporation	

15. BIBLIOGRAPHY

The following documents were consulted in the course of performing the UPTRSS study effort and preparing this final study report:

1. Chase, Wendell D. — Piloted Simulator Display System Evaluation — Effective Resolution and Pilot Performance in the Landing Approach. (NASA TMX No. 59806, Ames Research Center, California Accession Number N68-25339, Microfiche dated 6 July 1968)

2. MIL-T-9212B (USAF) — General Requirements for Aircraft Flight Simulator Trainer. 28 June 1967.

3. Christensen, K. K. and Johnson, L. L. — Study to Determine Methods of Simulating G Effects. Armour Research Foundation of Illinois Institute of Technology. October 1958.

4. UPTRSS Phase I Study Report

5. Link DLR 609 — Analysis of Brightness and Resolution Requirements for Visual Display. 1963.

6. T-37 and T-38 Aircraft Handbooks

7. T-4 and T-26 Simulator Handbooks

8. Lybrand, W. A., et al — Simulation of Extra-Cockpit Visual Cues in Contact Flight Transition Trainers

9. Steele, J. E. — Motion Sickness and Spatial Perception - A Theoretical Study. ASD TR61-530. Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio. November 1961.

10. Wendt, H. W. Operator Threshold Values Relevant for the Design of Moving Base Simulators. Link Engineering Report No. 763. Link Group of General Precision Systems Incorporated, Binghamton, New York 11 March 1966.

11. Meiry, J. L. The Vestibular System and Human Dynamic Space Orientation. NASA CR 628. October 1966.

12. Roscoe, S. N. "The Effects of Eliminating Binocular and Peripheral Monocular Visual Cues upon Airplane Pilot Performance in Landing". Journal of Applied Psyshology. Vol. 32., No. 6. December 1948. pp 649-662.

13. Dalto Electronics Corp. DEC 4000 Wide Angle Visual Simulation System - Undated, unnumbered proposal document of same name. Amplicon 260 - Dalto specification sheet No. DMS 3000-0167

14. Farrand Optical Co. "Farrand Facts - Pancake Window" data sheet (undated)

15. Bell Aerosystems Agena Electronic Image Generator Buffalo, New York

16. General Electric Company "Computed Display Fact Sheet", No. 3439-967-39A "Visual Simulation: Computed vs. Conventional" and No. 3439-967-39B both dated 3 October 1967 Monochrome System Specifications Model PD-700) No. GEA-8528(10M) 5-68

17. MGD Corp. "Description of Operation - Visual Display Projector" dated April 1966.

18. Hudson, E. M. Adaptive Training and Non-Verbal Behavior. NAVTRADEVCEN 1395-1. 1964

19. Flexman, R. E., et al. Synthetic Flight Training System. NAVTRADEVCEN 1948. April 1968.

20. United Aircraft Corporate Systems Center. Automatic Voice Display System Drawing No. 922116. 20 July 1966

21. MIL-STD-803. Human Engineering Design Criteria

22. Greenwood, D. T. Extended Euler Angle Coordinate System for use with All-Attitude Aircraft Simulators - Contract No. AF33(616)-5664 University of Michigan. 1962

23. Luxenberg, H. R. Display Systems Engineering New York: McGraw Hill 1967.

24. Poole, H. H. Fundamentals of Display Systems. Washington, Spartan, Brooks 1966.

25. Curry, William C. "CRT Displays" Modern Data System. September 1968.

26. Adams Associates. Computer Characteristics Quarterly 1968, Volume 8, No. 2.

27. Flexman, R. E., et al Evaluation of a Contact Flight Simulator When Used in an Air Force Primary Pilot Training Program. AFPTRC-TR-54-38

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13. ABSTRACT

In order to provide a sound basis for the preparation of specifications defining the requirements for and undergraduate pilot training research simulation system (UPTRSS), a comprehensive study was made of all aspects of current and projected simulator technology and those techniques of simulation and training which appeared to offer the greatest utility for research purposes were analyzed in detail to determine the form and extent of the capability in each area (e.g. aircraft systems, simulation, motion simulation, visual simulation) which should be specified for the facility. To assure the Air Force the widest possible latitude in its eventual selection of the capabilities to be provided in the facility, alternatives approaches of varying levels of complexity are described in a number of areas and the tentative preliminary design requirements set forth in each area are qualified as necessary to permit them to be considered in the light of subsequent decisions by the Air Force regarding research, objectives, training objectives, and level of expenditure

(Distribution of this abstract is unlimited).

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	ROLE	WT	ROLE	WT	ROLE	WT
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